1990/91

TECHNICAL REVIEW

CANMET

METALS TECHNOLOGY LABORATORIES

Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

Canada

THE ENERGY OF OUR RESOURCES, THE POWER OF OUR IDEAS

L'ÉNERGIE DE NOS RESSOURCES, NOTRE FORCE CRÉATRICE

Cover photograph
Scanning electron micrograph showing the fracture surface of a 6061 aluminum composite reinforced with graphite fibres

MTL 91-59(TR)

Cette publication est aussi disponible en français

For further information about
the Metals Technology Laboratories contact
Carole Champion
Chief, Technical Information Unit
(613) 995-8814

For information about joint business ventures
with the Metals Technology Laboratories contact
Jim Gilmour
Manager, Services to Industry
(613) 995-8006

Metals Technology Laboratories
568 Booth Street
Ottawa, Ontario
K1A 0G1
Fax: (613) 992-8735

TECHNICAL REVIEW

CANMET

W.H. Erickson
Director

R. Thomson
Manager
Technology Programs

A. Crawley
Manager
Laboratory Operations

J.B. Gilmour
Manager
Services to Industry

METALS TECHNOLOGY LABORATORIES

93-02628/

Mission

The Metals Technology Laboratories Division aims to enhance health and safety, and protect the environment by developing technology in partnership with industrial clients.

MTL strives to:

(a) increase the competitiveness of the Canadian metals industries;

(b) encourage the use of the best materials and engineering technology for improved reliability and productivity of mineral and hydrocarbon resource acquisition, processing, and transportation equipment; and

(c) enhance demand for products of the Canadian metals industry through commercialization of advanced materials and development of new products.

Foreword

Doing better with less! An overworked phrase perhaps but one that sums up MTL's achievements of the past few years. Increasingly it is valid as an exhortation to improved performance in the future. We have learnt that doing better with less is not only possible but is more fulfilling. A change to a high degree of team work, personal commitment, excellence and action-oriented management is critical in an era of competition for scarce resources.

The climate for change is truly remarkable. The PS 2000 thrust to revitalize the Public Service and the EMR Mission emphasizing staff involvement are major thrusts. MTL's change over the past three years to a client-driven program reflect the urgent need to contribute to Canada's competitiveness in world markets.

Next year will be MTL's 50th. year. Throughout its history MTL/PMRL has worked closely with industry. However, the challenge to visibly make a difference has never been greater, the need to be productive never clearer. Recently there has been a period of rapid change. Revenue from research now contributes significantly to our resources while formal research agreements with industry form the major part of our program. This high level of linkage with a tendency to focus on the short and medium term has increased our recognition that our exploratory research must generate the basis for new technology that can contribute to the future competitiveness of Canadian industry.

Doing better with less requires that we maintain a strong scientific reputation, build on partnerships and alliances with industry, sharpen up our business sense and strengthen our team. As this Report '91 clearly portrays, MTL is Canada's primary metals technology research and development centre. In partnership with our colleagues in industry and universities we aim to do better in the years ahead.

W.H. Erickson
Director
(613) 995-8248

Avant Propos

Faire plus avec moins! Une maxime surutilisée peut-être mais qui s'applique bien aux réalisations des Laboratoires de la technologie des métaux (LTM) dans les dernières années. C'est le précepte sur lequel se fondent de plus en plus les efforts portant sur l'amélioration continue de la performance. Nous avons compris qu'augmenter notre productivité en dépit des restrictions budgétaires est possible et combien plus valorisant. À une époque où les ressources existantes se raréfient et font l'objet d'une vive concurence, le travail d'équipe, l'engagement personnel et la gestion spécialisée, orientée vers l'action, sont essentiels à la survie des organismes.

L'époque actuelle favorise singulièrement le changement. Pour moderniser la structure gouvernementale, de nombreux efforts ont été faits. Au nombre des plus audacieux figurent FP 2000, projet de revitalisation de la Fonction publique, et la mission d'EMR qui vise la participation intégrale du personnel. Au cours des trois dernières années, les LTM ont modifié leur programme de façon à l'axer d'avantage sur le service à la clientèle, reflétant ainsi l'urgence d'accroître la compétitivité du Canada sur les marchés mondiaux.

L'an prochain, les LTM célébreront le 50e anniversaire de leur fondation. Depuis leurs débuts, les LTM/LRMP ont collaboré étroitement avec l'industrie. Cependant le défi de promouvoir cette collaboration de façon tangible et la nécessité d'accroître notre rendement n'ont jamais été aussi pressants. La période actuelle favorise les changements rapides. Les revenus générés par la recherche constituent maintenant une part importante de nos ressources tandis que les protocoles d'entente passés avec l'industrie relativement aux projets de recherche forment l'essentiel de notre programme. Cette collaboration étroite avec l'industrie et la tendance à réaliser des travaux à court et à moyen terme nous obligent à reconnaître que la recherche exploratoire est la pierre angulaire des nouvelles technologies qui permettront d'accroître la compétitivité de l'industrie canadienne.

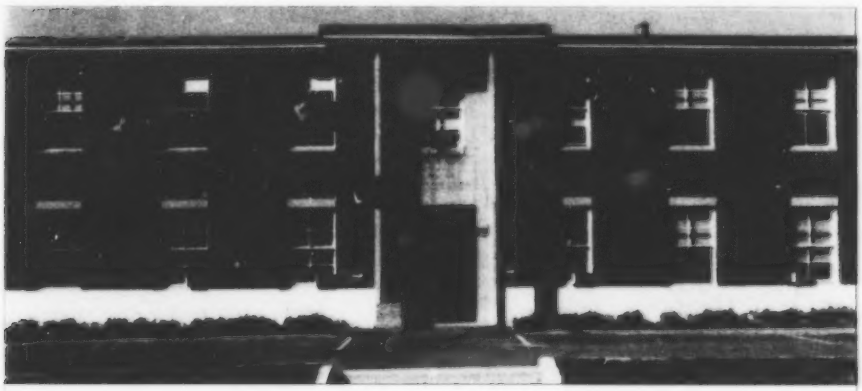
Faire plus avec moins est très exigeant. Nous devons maintenir notre réputation scientifique qui est fondée sur le partenariat et les ententes avec l'industrie, aiguiser notre sens des affaires et consolider nos capacités à travailler en équipe. Le Rapport annuel 1991 indique clairement que les LTM sont le centre par excellence de recherche et de développement technologique des métaux au Canada. De concert avec nos collègues de l'industrie et des universités, nous visons à faire encore mieux dans les années à venir.

W.H. Erickson
Directeur
(613) 995-8248

Organization

The Metals Technology Laboratories (MTL) perform research in Advanced Materials, Foundry Technology, Steel Technology, Materials for the Resource Industries and Non-Ferrous Products. To support these programs, the Laboratories are organized into five sections providing five areas of generic expertise.

MTL has a staff of about 120. Of these, about 45 are scientists or engineers and 50 are technologists or technical support staff. In addition throughout the year, MTL has some 25 visiting staff composed of students, post-doctoral fellows and workers from industry.



Director
W.H. Erickson

Technical Programs

- Advanced Materials
- Foundry
- Materials for Resource Industries
- Steel
- Non-Ferrous Products

Laboratory Operations

- Fabrication and NDE
- Foundry
- Metals Engineering
- Microstructural Characterization
- Engineering Performance

Technical Information Unit

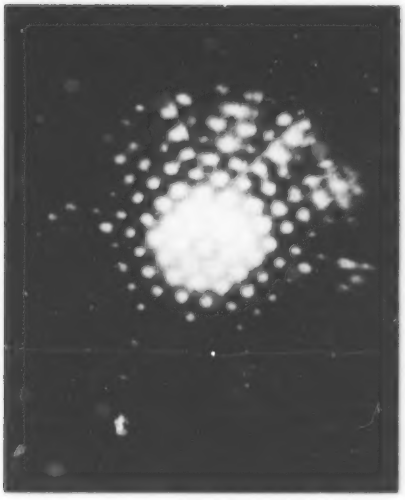
Services to Industry

- NDT Certification

Administration

Contents

1.	Advanced Materials	1
2.	Steel Technology	11
3.	Foundry Technology	19
4.	Materials for Resource Industries	27
5.	Non-Ferrous Products	39
6.	External Publications	41



1

Challenges and opportunities facing the advanced materials industry

- development of Al, Zn, Mg metal matrix composites for specific mass-produced products
- development of MMC technology
  - welding, joining to metals and ceramics
  - modelling of matrix/reinforcement interaction
  - recycling of MMCs
- materials engineering
  - near-net shape forming
- applications of nickel and titanium aluminides for high temperature use
- surface engineering
  - surface modification and coating technology
  - enhanced corrosion and wear resistance

Advanced Materials Technology

In recent years, world-wide attention has focussed on the development of materials with significantly enhanced properties or combinations of properties. Known generically as advanced materials, this development plays a critical pace-setting role in achieving society's requirements to cut energy costs.

Today's advanced material is tomorrow's commodity. "Tomorrow" can be a long time; on average, a decade elapses from the development to the retail of a new material. Exhaustive "fitness for purpose" testing has to take place to ensure that new materials have adequate physical and mechanical properties. MTL's advanced materials program seeks to assist Canadian industry in assessing the potential applications of advanced materials and to participate in the adaptation of new processing routes to commercial production.

Advanced Materials Technology

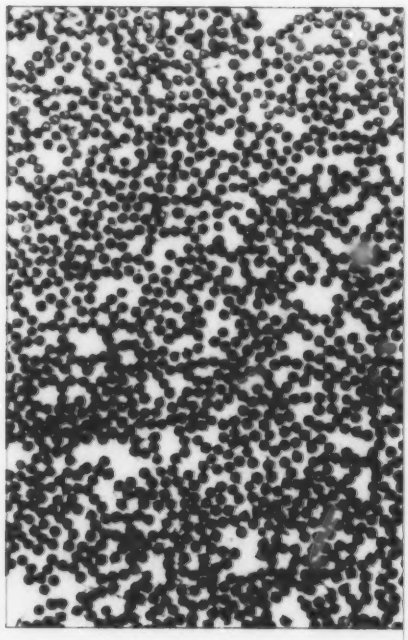
Metal Matrix Composites Improve Material Properties

Engineering materials may be divided into three classes: metals, ceramics and polymers. Each group has specific advantages and disadvantages. Metals exhibit strength combined with ductility and the ability to conduct heat and electricity but lack the high temperature strength, wear resistance and high elastic modulus of ceramics. However, ceramics lack the fabricability and inherent toughness of metals. To attempt to take full advantage of the properties of both classes of materials, metals producers are pursuing the development of metal matrix composites in which ceramic particles or fibres are embedded into the metal matrix. Properties such as elastic modulus, strength, wear resistance and elevated temperature properties can be significantly enhanced by combining these materials. A broad range of automotive, aerospace and communications applications are foreseen for high-strength, light-weight MMCs.

MTL's program is designed to provide technical assistance to industry in overcoming major MMC-production problems such as identification of suitable reinforcing agents for particular alloy systems, control of particulate/matrix interface reactions and development of uniform dispersions of particulates. A seven year program was initiated in 1988/89 to examine all aspects in the processing performance and application of metal matrix composites. Initially, zinc-, aluminum- and magnesium-based alloy systems have been targeted for development.

The core research on the wettability of ceramics by liquid metals, the performance of aluminum-based metal matrix composites, and the fabrication of MMCs by stir and squeeze casting has been complemented by extensive revenue-generating projects.

Cross-sectional view of C/Al composite reinforced with carbon fibres without any coating (X 100)



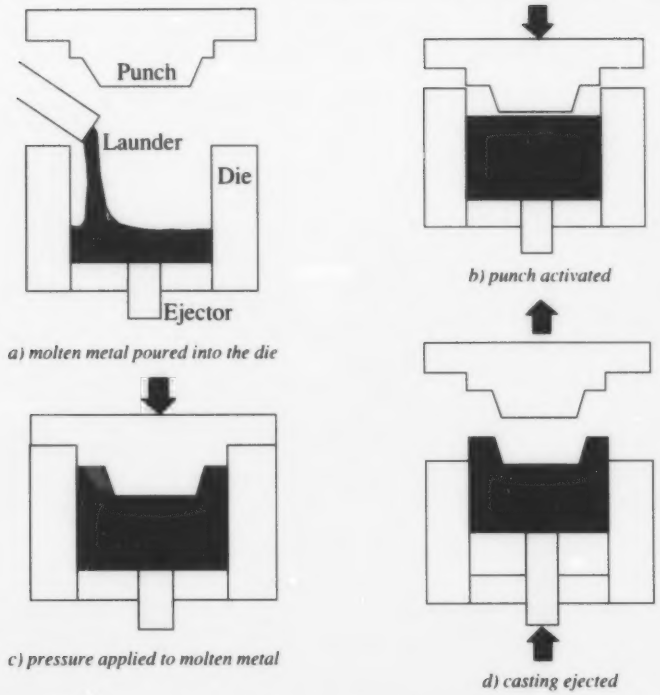
Cross-sectional view of C/Al composite reinforced with nickel-coated carbon fibres (X 200)

A comparative study was carried out on MMCs reinforced with nickel-coated and uncoated fibres. The beneficial effects of nickel coating in promoting wetting between the fibres and the aluminum matrix is evident. The carbon/6061 aluminum (C/Al) composite system is one of the most promising systems for aerospace applications. The work on C/Al composites was carried out under contract to INCO and MTL gratefully acknowledges their permission to use the photographs shown above.

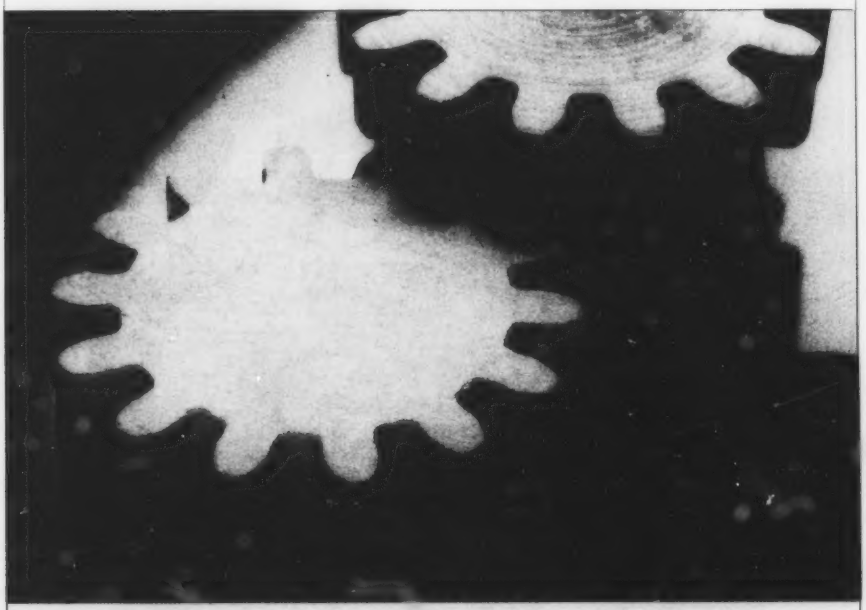
Wettability

In metal matrix composite materials, the nature of the contact between the ceramic reinforcing phase and the matrix must allow load transfer across the interface to achieve the material strength for which MMCs are designed. When strength is an important requirement, it is particularly important to have optimum stress transfer across the phase interface. It is known that the wetting of a solid by a liquid is closely related to the bonding across their interface. Good wetting is also a necessary condition for the generation of a satisfactory bond between solid ceramic particulates and the liquid metal matrix. However, ceramic/metal systems are typically non-wetting. Because wettability is crucial to successful MMC fabrication, a study of the sessile drop method, infiltration techniques, the dip coverage method and the impedance technique to evaluate the wettability of metal/ceramic systems was undertaken. In addition, a database for metal-ceramic contact angles has been compiled and a test unit has been built to provide a comparative evaluation of the wetting of the reinforcing phase with and without applied pressure.

Particle incorporation may be enhanced during the processing of MMCs by addition of alloying elements to the matrix metal, by surface treatment of the



Schematic of a squeeze casting operation



Gear casting produced by squeeze casting Zn-27%Al alloy into a glass fibre preform

reinforcing phase, and by application of physical force either by stirring or by application of pressure.

Of the methods available for fabricating metal matrix composites, casting processes stand out as one of the most attractive processing routes - potentially simple, and economical. Successful fabrication of particulate-reinforced MMCs by stir-casting depends on good wettability between the molten metal and the ceramic particulates. In stir-casting processes, shear forces generated by stirring help overcome the natural resistance of the ceramic particles to mixing with the molten alloy. The concerns which are encountered in stir-casting MMCs are wettability, melt fluidity and stirring action which, in turn, depend on several additional factors such as temperature, particle preheat, reactivity, stirring speed, stirring method and time. A balance of all these factors must be achieved to obtain a uniform dispersion of particulates throughout the liquid metal prior to casting.

Using zinc-aluminum alloys as the matrix material, a stirrer design for stir casting is being developed. Water modelling was used to optimize the design, based on the criteria of maximizing shear rate in the liquid while, at the same time, minimizing the entrapment of gas bubbles into the melt.

Squeeze casting provides an alternative to stir casting for production of complex shapes and when ceramic/metal systems with limited wettability are to be employed. The application of high pressures (>70 MPa) is sufficient to force contact between the molten metal and the reinforcing phase. Critical to the production of squeeze-cast composites is the ability to produce a ceramic preform suitable for metal infiltration. MTL has

developed an improved technique for fabricating such preforms which is now the subject of a patent application.

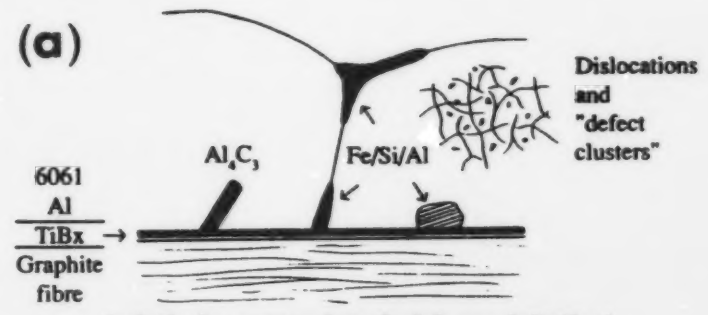
Aluminum-Based MMCs

To supplement the existing data on commercial aluminum-based alloys, an evaluation of the engineering performance of these materials is underway. Typically, the ductility of silicon carbide reinforced aluminum alloys is an order of magnitude less than that of the unreinforced alloys. For this reason MTL studies are focused on the effects of heat treatment and volume percent of silicon carbide on the microstructure and tensile properties of powder-metallurgy-fabricated MMCs based on alloys 7091 and 6061. At this interim stage of the work, the data suggest that the tensile property response of the MMCs to ageing heat treatments is very similar to that of the matrix itself, although in the later stages of deformation cracking and decohesion of the SiC particulate is always observed.

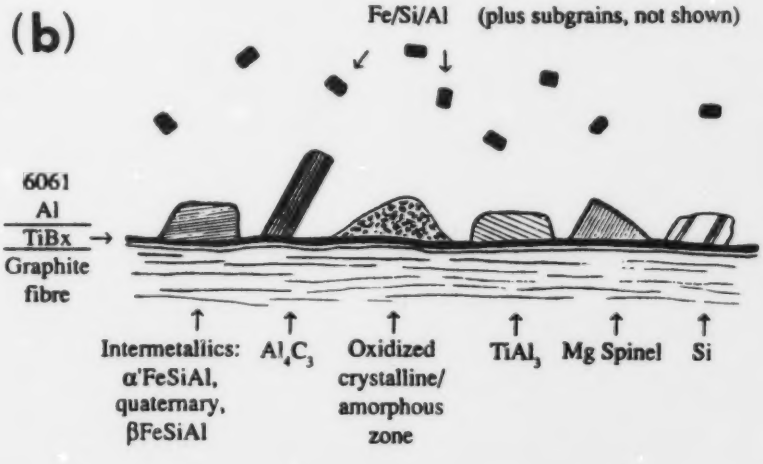
Phase Identification in Graphite Fibre/Aluminum Composites Using Analytical Electron Microscopy

The high specific strength, high modulus and low coefficient of thermal expansion of graphite fibre-aluminum (Gr/Al) composites have resulted in their use for components in space structures. However, the exposure to high temperatures required for the production of bulk material can result in interfacial reactions that cause a degradation in mechanical properties. Analytical electron microscopy (AEM) has been used to examine the phases formed during the heat treatment of such materials. The Gr/Al composite was examined in two forms: (a) as wire tows made up of AA6061 Al alloy, reinforced with Arco pitch-based P100 graphite fibres, coated with a thin layer of TiB_x, and (b) as bulk composites produced by hot pressing a bundle of tows within a cladding of AA6061.

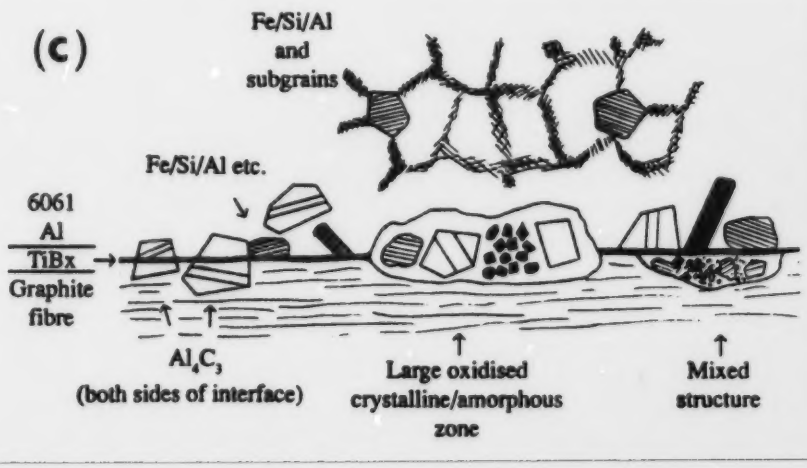
In the tow material, only limited precipitation of Al_4C_3 was present at the fibre/matrix interface, together with some intermetallics at the matrix grain boundaries. In the bulk composite, the results of the extra high-temperature processing stage were apparent. The



Schematic of the as-received tow

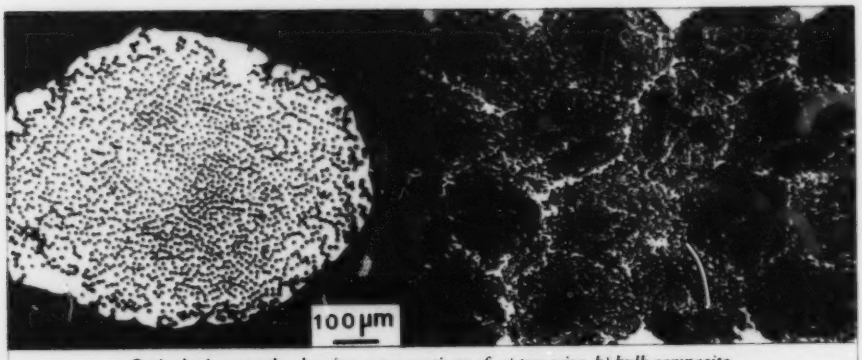


Schematic of the matrix/tow interface after an intermediated heat treatment between 580-600°C

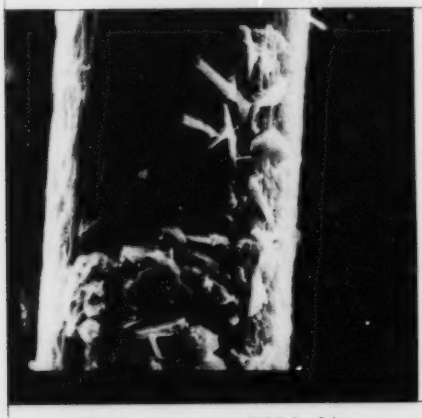


Schematic of the matrix/tow interface after a high temperature heat treatment between 650-700°C

Schematic diagrams illustrating the phases and microstructures observed in graphite/aluminum composite specimens after being subjected to different heat treatment conditions.



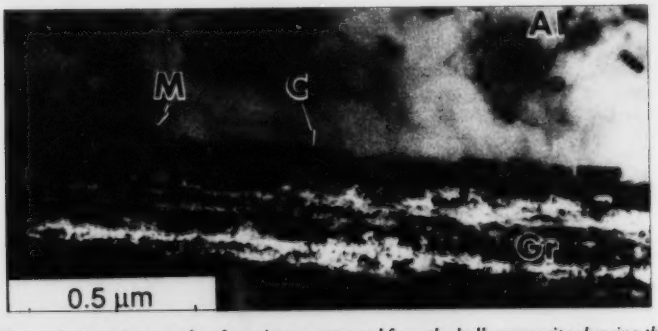
Optical micrographs showing cross-sections of a) tow wire, b) bulk composite



Tow heat treated at 630°C for 2 h

Tow heat treated at 650°C for 2 h

SEM micrographs of graphite aluminum tows etched in HCl/H_2O



Transmission micrographs of specimens prepared from the bulk composite showing the presence of α'FeSiAl intermetallic particles in the matrix and various precipitates at the fibre/matrix interface. M = Mg spinel, C = Al_4C_3

Transmission electron micrograph of a cross-section of a graphite/aluminum composite, showing the precipitation of various phases at the fibre/TiBx/matrix interfaces, induced by heat treatment for 2 h at 580°C.

matrix contained a high density of α'FeSiAl precipitates, ~50 nm in diameter. Precipitation at the fibre/matrix interface was considerably more advanced than in the tow material. Precipitates were identified as Al_4C_3 platelets and α'FeSiAl, in approximately equal numbers.

Heat treating both materials at temperatures in the range 580°C to 700°C resulted in increasingly severe interfacial reactions. The phases that were positively identified at the interfaces of heat-treated samples included the following: (a) rhombohedral $Al4C_3$, having a random orientation relative to the Al matrix, (b) bcc α'FeSiAl, (c) fcc Mg spinel, $MgAl_2O_4$, (d) elemental diamond cubic Si, (e) bct $TiAl_3$, both as large crystals and as fine precipitates within an amorphous oxide reaction zone, (f) fcc MgO (periclase), in the form of fine crystals in an amorphous reaction zone, and (g) an intermetallic phase having the hexagonal structure reported for a quaternary phase, $FeMg_3Si_6Al_8$.

Ultramicrotomy for Materials Science

Diamond knife sectioning, or ultramicrotomy, is a new technique for producing very thin (10 µm) electron-transparent samples for microstructure characterization. The technique, which has now been applied to a wide range of materials including metals and alloys, ceramics, composites, glasses, minerals and polymers, can produce specimens free from deleterious artifacts arising from conventional thinning techniques which limit the ability to perform accurate chemical microanalysis.

An MTL scientist has had a major review published by the Materials Research Society, Pittsburgh, 1990, of more than three decades of work on ultramicrotomy, including the results of several years of collaborative work with Alcan. This review provides the first attempt to describe a basic methodology for ultramicrotomy in materials science and includes many unpublicized and ingenious applications. Since "Ultramicrotomy for Materials Science" appeared in print it has been in great demand by

instrument manufacturers and a variety of research institutes and more than 1 000 copies have been distributed worldwide. Largely as a result of this review, the topic has been included in several international workshops and short courses on electron microscopy.

Surface Modification

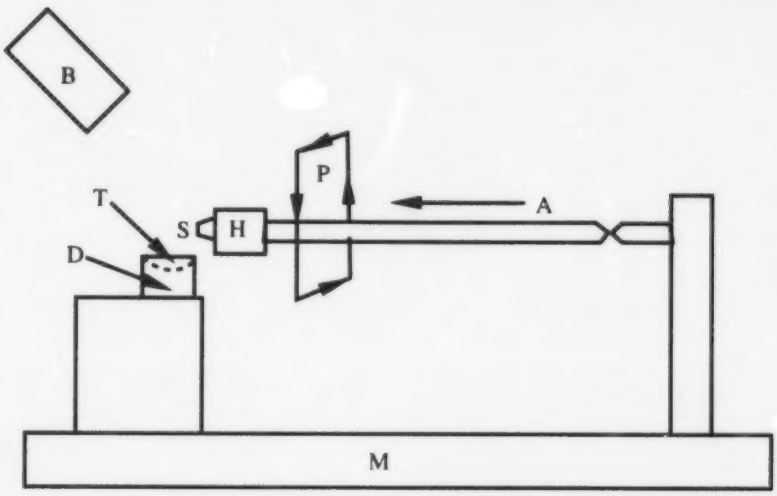
To benefit Canadian metal producers and users, specifically those involved with aerospace materials, machine tools, injection moulds, medical protheses and corrosion-resistant automotive parts, MTL is identifying specialized processing techniques that are likely to become important to industry in future years. The advanced surface modification of metallic surfaces leading to improved wear resistance, corrosion resistance, adhesion to other surfaces, reduction of friction and aesthetic appearance falls into this category. Processes such as ion beam implantation, ion nitriding, thin film deposition and laser modification are attracting considerable attention abroad and have in many cases been brought into routine production.

A surface treatment questionnaire was sent out to industry to determine who may benefit from the adoption of one of the advanced surface modification techniques to improve specific engineering products. The positive response to the questionnaire ensures MTL's technical contribution in meeting Canadian industrial demands.

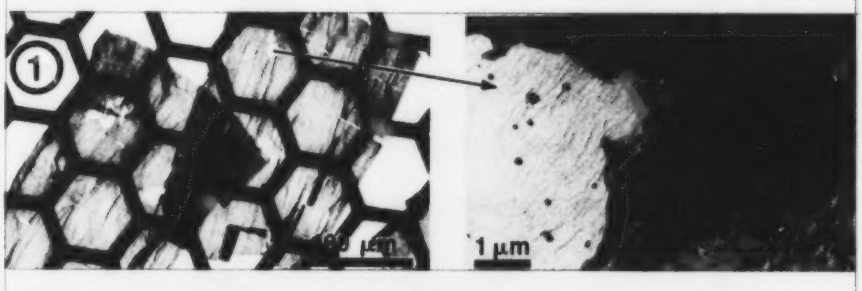
Investigation of Silicide Contacts to Aid Miniaturization of Electronic Devices

Metal silicides are grown onto silicon wafers for the purpose of making electrical contacts. As device sizes shrink, the structure of these intermetallics becomes increasingly important, and the correct choice of metal depends not only on its reaction with silicon but also with electrically active dopants and other impurities.

Under a joint agreement, Northern Telecom and the Metals Technology Laboratories joined forces to study the effect of silicide growth on the arsenic profile in previously implanted silicon wafers.



Basic components of a modern ultramicrotome, with specimen S in holder H mounted on an arm A. The arm moves by a set amount and down onto a diamond knife set in a mount D and retracts (path P). This produces a thin section which floats on a liquid in the trough T. The process is observed through a stereo microscope B, with illumination from above and below the knife/specimen region. The instrument rests on a rigid base M and is otherwise protected from vibration.



A certain amount of methodology development is required for each new material that is diamond sectioned. Work done for the International Magnesium Association illustrates this point well. The reactivity of magnesium to water, the normal sectioning liquid, necessitated dry sectioning and the careful manipulation of very light (nanogram) sections onto copper grids. However, it was found that the sections did not lie flat on the grid unless briefly wetted. Photograph 1 shows that methonol wetting caused dissolution of the magnesium matrix in places, leaving an oxide "bag" holding matrix precipitates in between. This artefact may play a useful role in studying the air-formed oxide or in more accurate microanalysis of magnesium-containing precipitates. Useful cross-section corrosion films were produced (2) which clearly show i) the corrosion film, ii) the presence of deep pores in the magnesium and iii) no obvious iron impurity concentration anywhere in the film. The sections were produced without embedding in epoxy resin, thus reducing normal specimen preparation time to a matter of a few hours against 2-3 days for normal transmission electron microscopy samples.

Ion Beam Modification of Metal Surfaces

The benefits of ion beam modification arise from one of several processes, including ion implantation, ballistic mixing and controlled radiation damage. Ion implantation introduces foreign atoms to a depth of approximately a micron, depending on the energy and mass of the projectile. Ballistic mixing causes enhanced diffusion of atoms in the surface region . Radiation damage can cause hardening, or the formation of defect structures such as vacancy loops. Despite the limited depth of the implanted ions, improvements in the wear resistance often extend to far greater depths.

Properties that can be improved by ion beam implantation
- wear resistance, surface hardness
- spallation resistance of surface oxides, particularly for stainless steel
- coefficient of friction
- corrosion resistance
- adhesion of deposited thin films
- mixing of normally immiscible elements in a thin film
- chemical composition and microstructure of deposited coatings
- colour and appearance
- catalytic properties

Particular advantages of ion-beam modification
- independent control of penetration depth
- use of controlled temperatures (frequently room temperature)
- no alteration of sample dimensions, may be applied to finished products
- extremely fine microstructure developed
- clean vacuum process, in situ surface cleaning by sputtering may be possible
- non toxic, conserves materials
- mixing of normally immiscible elements, concentration not limited by solid solubility
- wide range of implant species available (almost the whole periodic table)
- implants can be isotope specific

Applications of ion-beam modification
- increased lifetime of tools used for injection moulding of plastics
- superior biomedical components, especially hip and knee prostheses
- stronger motor crankshafts in automobiles, and gears in aircraft engines
- harder industrial knives and cutters, improved drill bits
- longer-lived precision rollers, metal punches, extrusion dies and forming tools (by factors of four to twelve)
- superior ball bearings for navigational instruments in aircraft and for jet engines
- formation of lubricious oxides on ceramics
- reduction in oxidation of fuel-cladding stainless steels
- improved coatings on turbine blades
- improved adherence of coatings on steel and aluminum moulding tools
- corrosion inhibition in surgical titanium alloys
- colouring of boron-rich films on metal substrates
- improved wear resistance of contacts and switches in microelectronic circuits
- improved catalytic behaviour

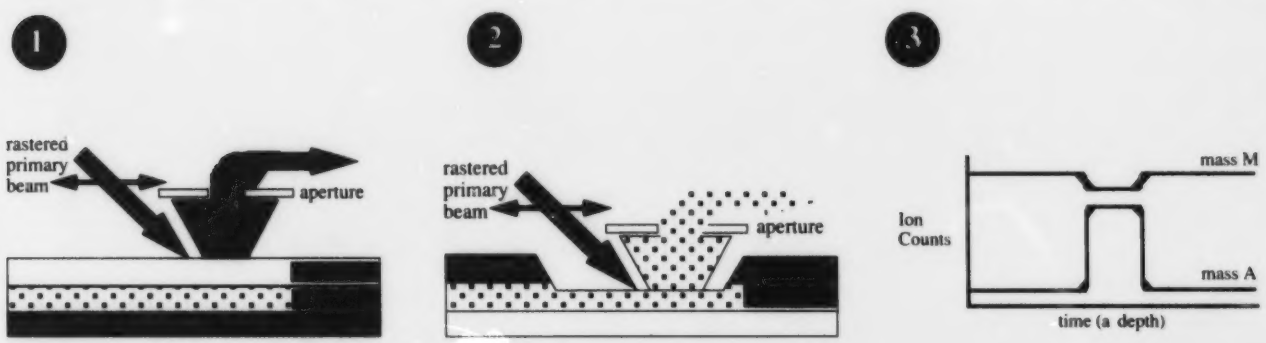
Laser Modification of Metal Surfaces

Laser technology offers a means of depositing large amounts of thermal energy in a highly localized area. The beneficial effects of laser treatment arise from the microstructural modification of surface layers of material which can result from laser annealing, transformation hardening, surface melting, cladding or particle injection treatments.

Properties that can be improved by laser treatments
- wear resistance, hardness and fatigue life
- corrosion and oxidation resistance
- coefficient of friction
- adhesion of deposited films or powders
- degree of surface alloying, bonding between adjacent parts (welding)
- surface microstructure (grain refinement, metastable phases)
- soft magnetic properties
- catalytic activities

Particular advantages of laser processing
- highly localized, controlled heating
- low heat input and energy use
- melting or annealing of surface film while bulk material is unaffected
- short reaction times produce high quench rates and prevent loss of volatile elements
- ability to perform very fine-scale welding with minimum distortion
- can be used in combination with thin film growth or powder deposition to produce metastable alloys while conserving costly alloy additions

Applications of laser processing
- hardening of steel engine bores, valve seats and steering gear housings
- hardfacing of pump valve seats and blades for steam turbines
- formation of boride-containing eutectic coatings for hardfacing or ferrous alloys
- cladding of low-carbon steels by injecting SiC particles onto the laser-generated melt pool
- improved wear and corrosion resistance of Ni and Ti alloys for turbine blades in electrical steam generators
- surface coating of Al alloys with high Si content for improved wear resistance
- surface cladding of Mg alloys with Al, Zn or rare earths for enhanced corrosion resistance
- formation of glassy metal coatings on ferrous alloys for high corrosion resistance in chemical applications
- formation of amorphous coatings for improved catalytic capability
- formation of glassy metal coatings for hydrogen evolution electrodes
- formation of ohmic contacts on GaAs or Si for microelectronic applications
- cladding of powder silver on copper for electrical contacts
- formation of amorphous diffusion barriers in electronic packaging
- formation of thin optical or magneto-optical coatings
- scribing of electrical steels to enhance soft magnetic properties
- specialized welding procedures such as galvanized sheet with localized zinc evaporation



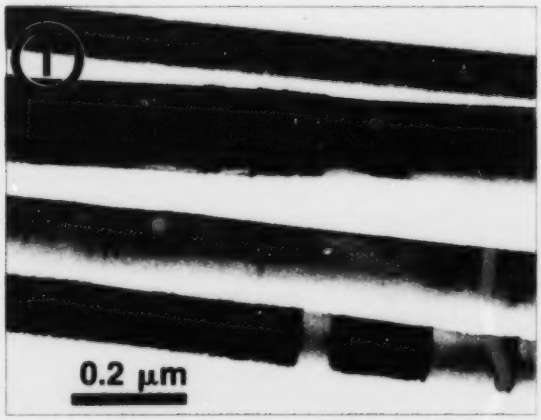
Secondary ion mass spectrometry (SIMS) has emerged as an extremely useful technique to obtain depth profiles of compositional variations in the near-surface region (1-100 μm) of many materials. Its particular advantages are sensitivity, depth resolution, large dynamic range and the ability to detect all elements in the periodic table.

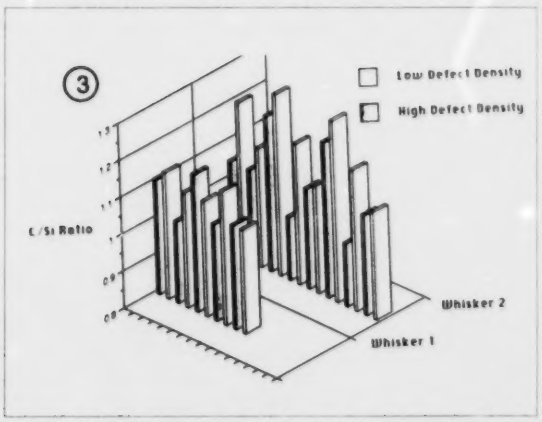
The normal surface analysis techniques of sputter depth profiling are confounded by the continual forward mixing of certain elements during ion bombardment as a result of segregation away from the implanted atoms. This process can cause a severe distortion of the true profile, particularly when sputtering from high to low concentration regions. Therefore, it is be difficult to study the behaviour of elements immediately underlying a silicide film if the metallic atom in the silicide is prone to such segregation. To combat this problem, a back-thinning technique was developed to strip the substrate away by polishing and selectively etching so that the semiconductor/metal interface could be approached by sputtering from the back side.

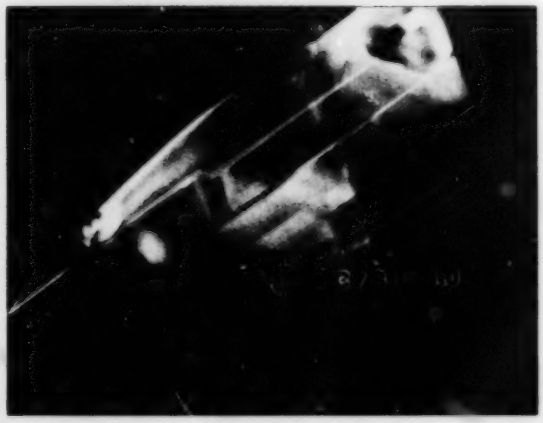
Secondary ion mass spectrometry (SIMS) has emerged as an extremely useful technique to obtain depth profiles of compositional variations in the near-surface region (1-100 μm) of many materials. Its particular advantages are sensitivity, depth resolution, large dynamic range and the ability to detect all elements in the periodic table. In the case of silicide contacts, SIMS depth profiles of the back-thinned wafers was carried out and front- and back-side profiles of the samples revealed a dramatic improvement in depth resolution when profiling from the back-side. These are the first results obtained using this technique on silicon to profile dopant redistributions in silicide films, and should allow more detailed studies of silicon/silicide interfaces in the future.

Development of Improved-Quality Rare Earth Magnets at Reduced Cost

Since their initial discovery in 1982 and commercialization in 1984, the use of iron-neodymium-boron (FeNdB) magnets expanded rapidly, attaining annual growth rates in excess of 100% in recent years. The high magnetic strength of these alloys compared with conventional ferrite and AlNiCo magnets, and their low cost compared with CoSm magnets of comparable strength have been responsible for this dramatic growth. By the year 2000 FeNdB magnets are expected to achieve a 40% share of the permanent magnet market and sales of between $1 and $2 billion are projected.

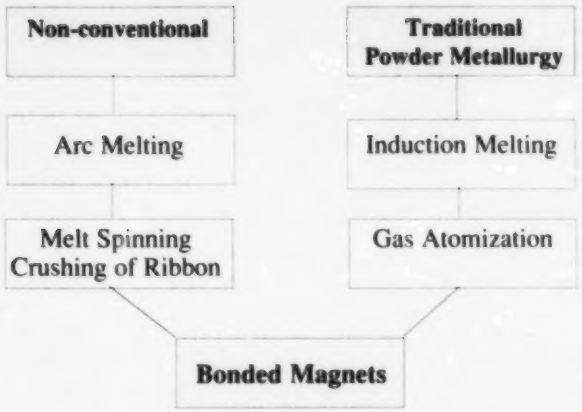






In response to the Canadian resource industries diversifying into non-metallic materials and metal/non-metal composites, MTL undertakes microstructural and mechanical characterization for determination of structure/property relations. In cooperation with Ceramics Kingston, silicon fibres have been characterized to develop catalyst/fibre growth models. High resolution transmission electron microscopy combined with crystal structure data from microdiffraction (including MTL-derived diffraction programs) and microanalysis using electron energy loss spectroscopy (EELS) demonstrated fibre growth of silicon carbide whiskers.

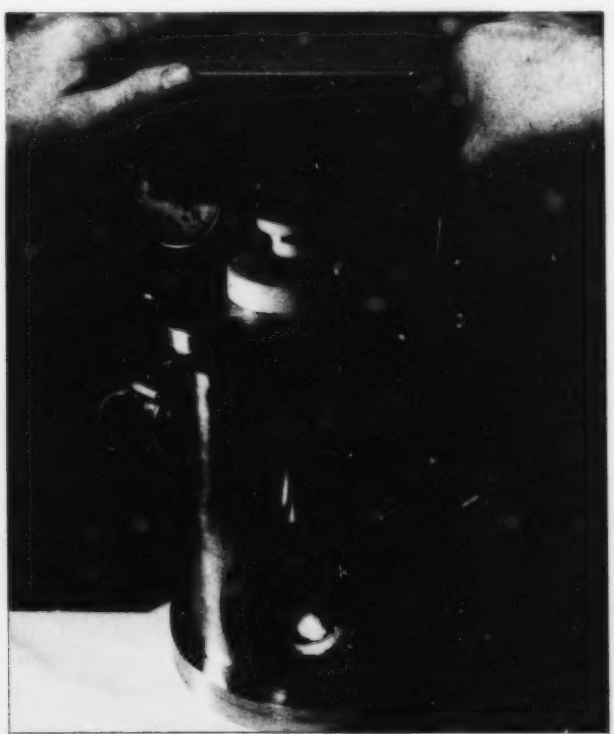
Photograph 1 shows the fibres contained regions of low and high densities of planar defects. On closer examination (2) the planar defects can be seen to be closely-spaced thin regions of different crystal structure which could have a lower fracture resistance or surface adhesion to the matrix in which the fibres were embedded. EELs showed there was a small but consistent C/Si ratio difference from low to high defect density regions (3) which favoured a model of small perturbations in vapour deposition onto the growing fibre causing the transition from one type of region to the other. Ultramicrotomed cross-sections (4) showed that the fibre composition was stoichiometric in the fibre centre. This indicates that the non-stoichiometric EELs readings on fibres like those in (1) are due to an unsuspected thin, carbon-rich coating on all fibres - an important consideration for matrix adhesion.



Comparison of traditional powder metallurgy route for production of bonded magnets with melt spinning.

The drive to reduce vehicle weight to improve fuel efficiency in the transportation industry is in part responsible for this high demand. The high magnetic strength of FeNdB magnets allows miniaturization of magnetic components thereby reducing size and weight. Production of high-strength magnets in the form of flat strip, ring and discs will allow redesign of motors and transducers to take full advantage of these benefits. There is also great demand for the miniaturization of magnetic components for electronic and communications applications.

Three types of FeNdB magnets are currently produced: bonded, hot-worked and sintered. MTL work is focussed on bonded and hot-worked magnets. The permanent magnet program which began in 1988 was designed to have a five-year life span. In-house research has resulted in the development of techniques to cast, fabricate and characterize FeNdB magnets.

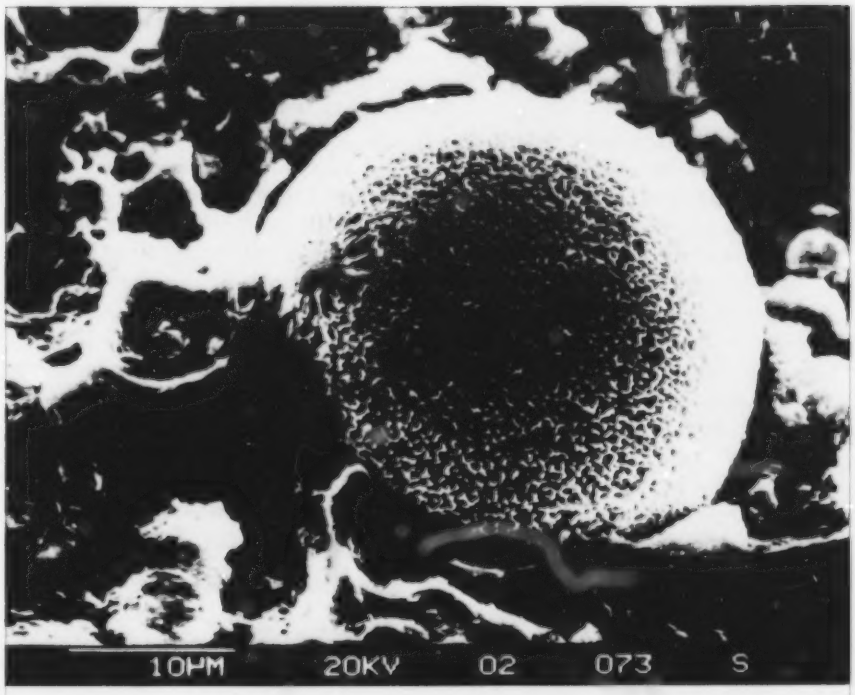


Arc melting furnace used for preparation of small quantities of high-coercivity magnetic alloys as a first step towards producing high-strength magnets by melt spinning.

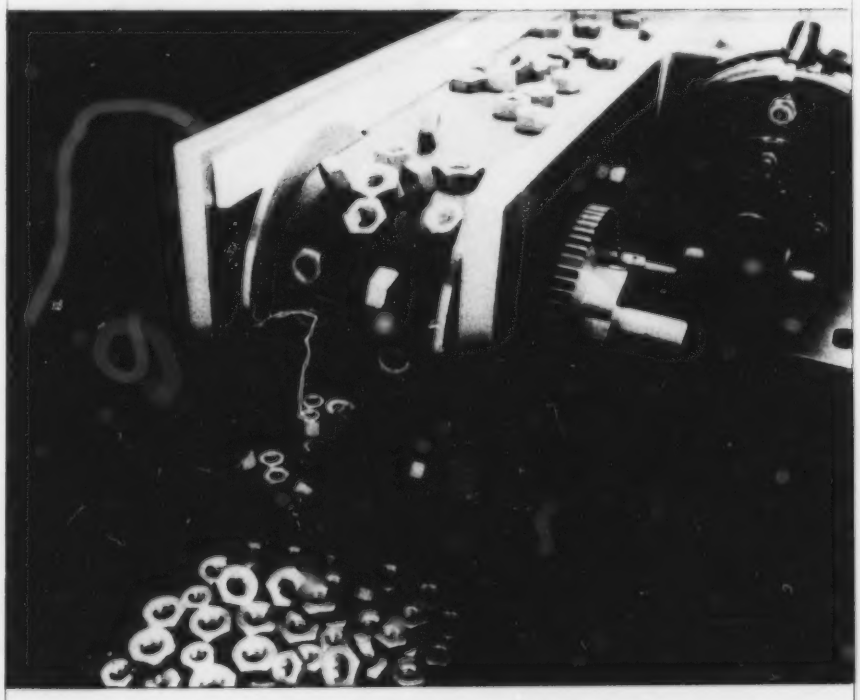
High-strength FeNdB magnets are currently produced from ground FeNdB powders via a complex sintering process. Sintered magnets currently sell at about $ 200/kg whereas the raw materials are worth about $ 60/kg. The high cost of sintering offers considerable scope to develop hot-worked magnets by lower-cost production routes such as conventional ingot casting and rolling. Hot rolling also offers the opportunity to develop the crystallographic textures necessary to further enhance magnetic anisotropy and thus magnetic properties. Preliminary hot-rolling trials on arc-melted FeNdPrB and FePrB ingots has demonstrated that large, single-pass reductions, 50% at 1000°C, can be tolerated. In addition, FeNdB compositions have been cast and rolled in multi-pass reductions which results in the grain refinement necessary to produce good magnetic properties.

The production of polymer-bonded magnets depends on the availability of suitable magnetic powders. To date, much of the powder has been produced commercially by grinding melt-spun ribbon or flake. At MTL, gas atomization, an established powder metallurgy technology, has been explored as a low-cost alternative to melt spinning for preparation of high-coercivity FeNdB powders. Fine (60 µm) spherical powders of a proprietary compostion have been prepared by high-pressure gas atomization. Annealing to enhance the grain structure improves the intrinsic coercivity of the powders, H_{ci}, a further 37%. Bonded magnets in the form of strip 100 mm square by 1 mm thick produced by injection moulding exhibit an energy product (BH_{max}) of 2.45 MGOe, coercivity (H_c) of 10 kOe and remnance B_r of 3 kG.

MTL's knowledge of magnet technology has been used to assist various industrial clients. In one project, a study was conducted to assess the effects of impurities on magnet properties. MTL has also provided technical assistance to the Mineral Sciences Laboratories of CANMET in developing a magnetic garbage separator under contract for Alcan. A similar project will examine the feasibility of developing a rotary separator using high-strength magnets for reclaiming foundry sand.

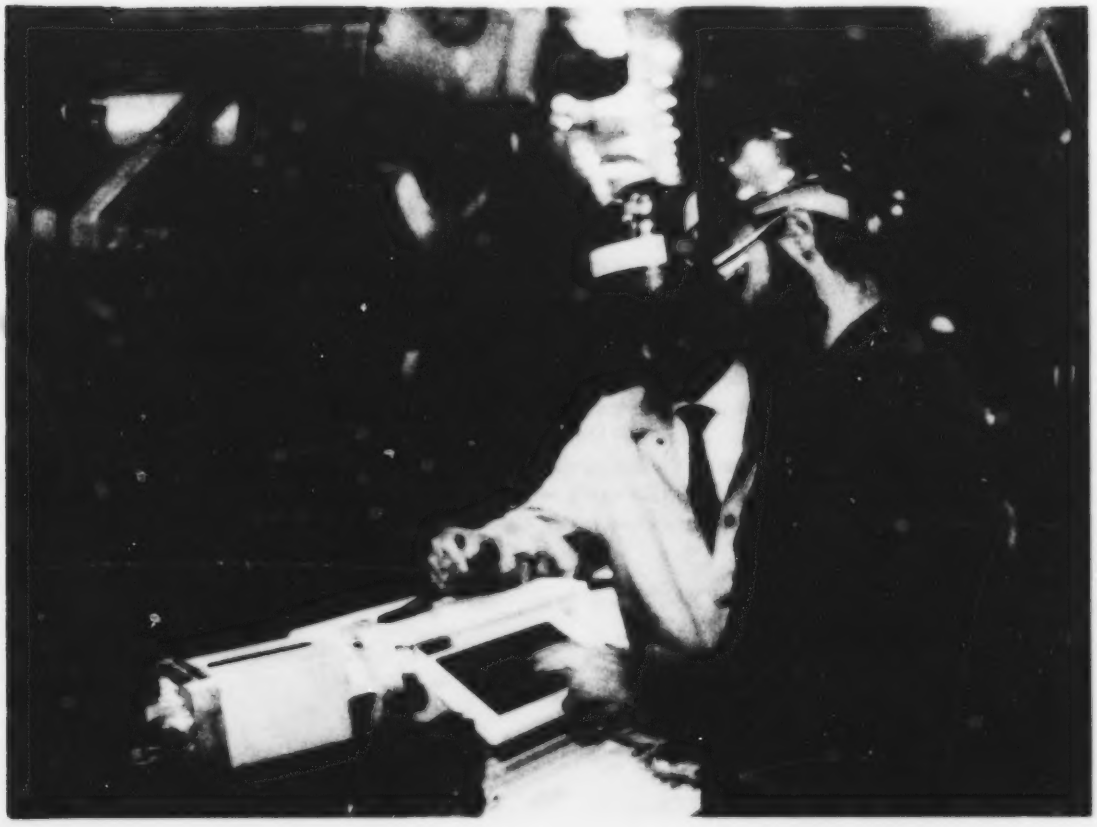


Microcrystalline particle of atomized FeNdB alloy. The single particle is composed of one million ultra-fine magnetic grains separated by thin non-magnetic walls.



Prototype magnetic separator that uses MTL NdFeB magnets. Work is about to begin on a rotary separator that makes use of high strength magnets, for cleaning foundry sand

Steel Technology



The Canadian steel industry is confronted with increasingly stringent process and product specifications while having to reduce costs to be competitive. Reduction in industry research facilities, new iron-making processes, the growth of mini mills and scrap remelting, introduction of commercial strip casting and application of expert systems are challenges facing the industry in the nineties. MTL performs collaborative work on casting, coating, forming and the metallurgy of steels in support of the industry's goal to enhance its global competitiveness.

Continuous Casting Technology

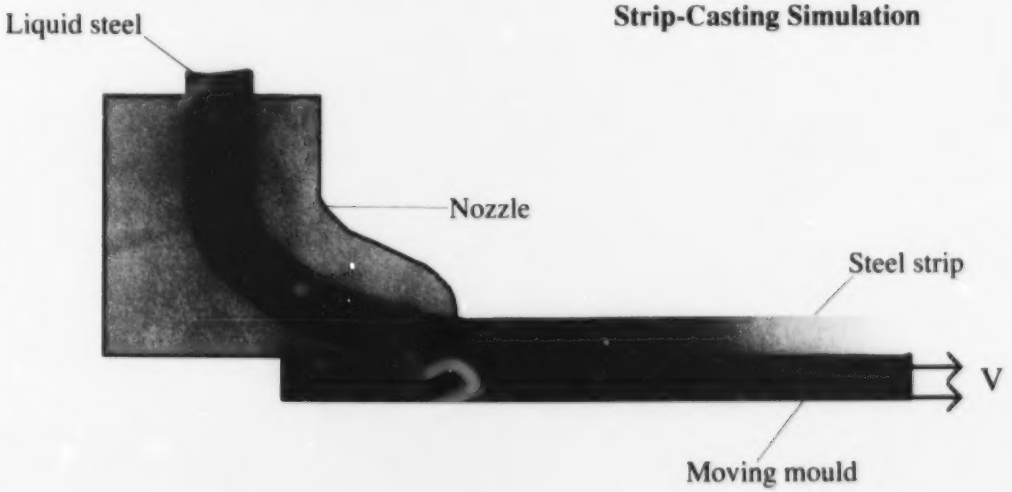
Direct-Strip Casting to Save Energy and Money

Steel industries around the world are looking for ways to convert liquid steel to near net shape products in the smallest number of processing steps. The direct casting of thin steel strip eliminates many of the processing steps needed to make hot strip thereby greatly reducing the cost of the final product.

MTL has a flat-bed strip casting simulator which can be used to cast steel plates 150 mm wide, 400 mm long and 2 to 10 mm thick. Previous exploratory work using this simulator to produce steel strip, using a controlled pouring stream intersected by a moving copper plate mould, was used as a starting point to design and water model a pneumatic liquid-flow control system. A fully instrumented machine is under construction to establish techniques for casting and solidifying steel strip and thin slabs under conditions of heat transfer, solidification rate and reoxidation protection found in an industrial-scale plant. The effect of these process variables on the quality of the cast strip and on the properties of the steel after hot and cold rolling will provide guidance in the design and operation of machines for pilot-scale strip casting. MTL's single wheel caster, the design of which is being used by a major non-ferrous producer, is being upgraded to include reoxidation protection.

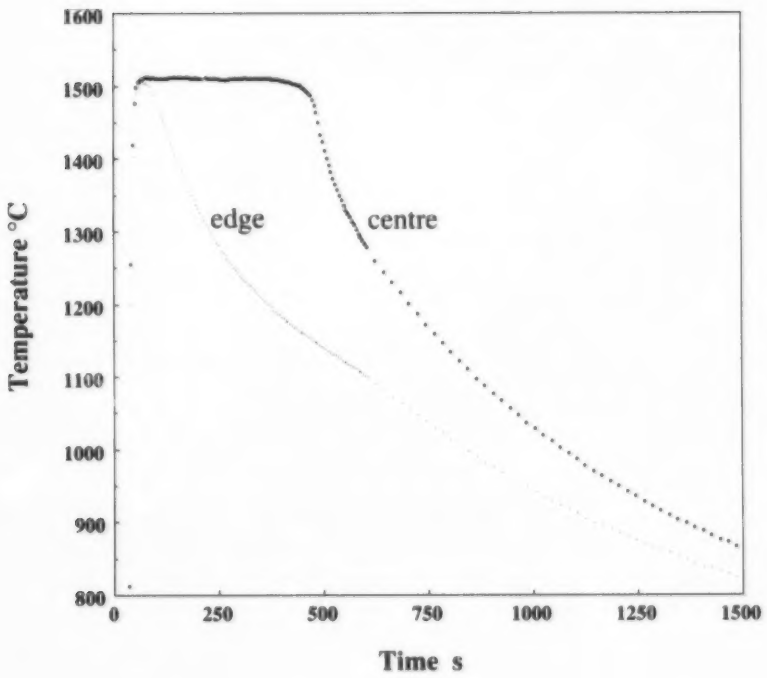
Projet Bessemer Inc. has the mandate to develop strip-casting technology in Canada to enable the Canadian steel industry to compete with third-world low-cost producers. The thrust of MTL's simulation work is to establish and replicate the thermal history of steel being processed in several generic types of moving-mould strip casters. By so simulating production, the interfaces between composition, microstructure, hot and cold rolling and sheet product properties may be quantified efficiently and effectively without resort to casting

Strip-Casting Simulation



The strip casting process is simulated to ascertain:

- Conditions for high quality products
  - heat-transfer coefficient
  - laminar velocity of the liquid
  - speed of the mould (V)
  - superheat of the melt
- New chemistry
- Optimization of thermomechanical processing



Temperature profiles during solidification at the centre and near the surface edge of a 40 kg steel ingot, 120 x 150 x 270 mm, cast in a permanent cast-iron mould, to simulate continuously-cast billet. The pouring temperature was 1580°C. Steel composition: 0.28C, 0.34Si, 1.30Mn, 0.008Si, 0.016P, 0.042Al

machine construction. This work complements the caster hardware focus of Projet Bessemer's long term objectives.

Increased Productivity by Direct Rolling of Concast Billet

The direct rolling of concast billet has been identified by the Canadian Steel Industry Research Association (CSIRA) as a strategic activity within its long-term plan. At present there is no direct rolling of concast billet in North America, but large cost savings in time and fuel and an increase in productivity would be realized by this process.

Continuously-cast, special-bar-quality steel billets, with and without a brief homogenization intermediate heat treatment, have been direct rolled at MTL to simulate the conditions for conventional charging and the direct rolling route. The solidification rates in a 120 mm square billet solidified in a cast-iron mould are similar to published values for concast products. The Gleeble 1500 thermomechanical simulator was used to establish the effects of casting and cooling rate, and reheating on precipitate distribution before rolling so that appropriate conditions for direct rolling, such as the reheat temperature, could be determined.

The aim of the laboratory simulation work is to establish the viability of direct rolling concast billet commercially.

Flat-Rolled Products

Sheet

Formable Steels for Car Bodies

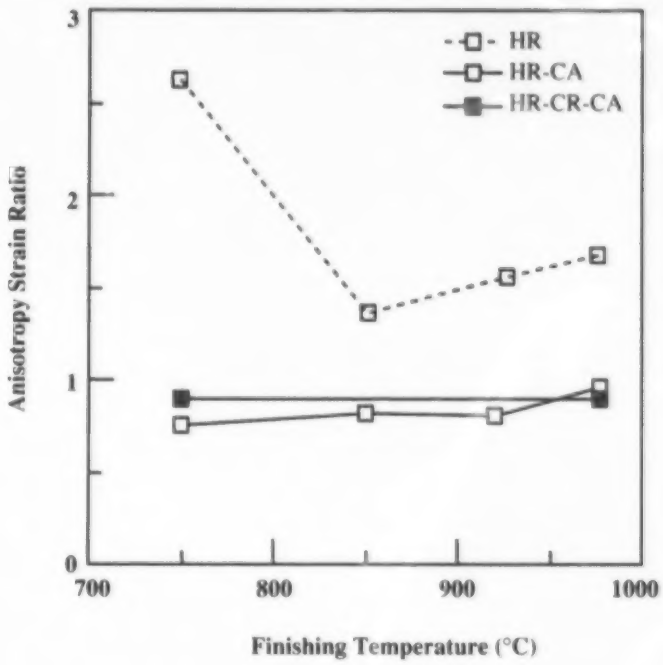
Interstitial-free (IF) steels are a new grade of steel much in demand by the automotive industry for forming into body panels. Recent tests in Japan indicate that titanium-stabilized interstitial-free steels with 30 ppm of carbon and nitrogen demonstrate consistent mechanical properties. As a result, many steel producers are making and processing IF steels as a replacement for aluminum-killed drawing quality and deep-drawing quality steels. To satisfy the demands for high-strength steels with good formability, Japanese producers have developed extra deep-drawing

quality IF steels by adding Mn, P, Ti, Nb and B.

As with most new products there are some production problems which include the sensistivity of the material to surface conditions, variation of texture and mechanical properties across the thickness in thin hot gauge band. To solve some of these production problems MTL is developing new grades of deep-drawing quality IF steels to determine the optimum compositions and processing parameters for batch- and continuous-annealing cycles. This knowledge will facilitate the production of hot- and/or cold-rolled IF steel sheet with specific chemical compositions to meet the property requirements for deep-drawing quality, extra deep-drawing quality and in higher-strength steel grades.

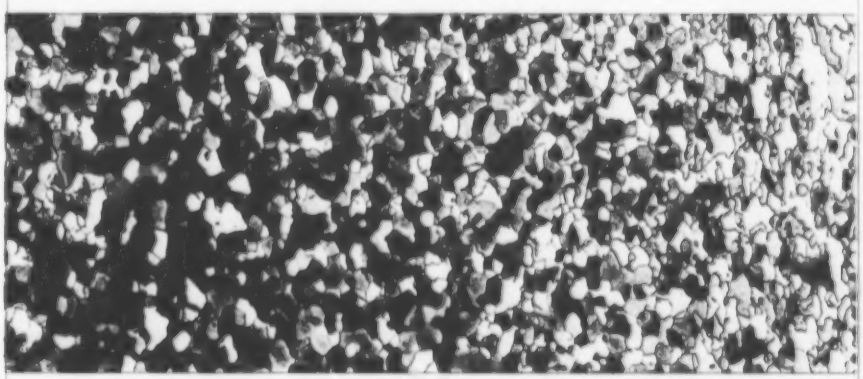
MTL and Dofasco Inc., Canada's largest steel producer, signed a major joint agreement to develop the compositions and processing schedules for interstitial free (IF) deep-drawing quality sheet. To detail the evolution of texture in IF steels, five compositions have been cast and rolled on the MTL pilot mill over a range of reheat and finishing temperatures. It was shown that the Ti-bearing IF steels showed little differences in response to reheat and finish temperatures after hot and warm rolling and continuous annealing. However, one particular processing schedule produced an r value of 2.6 and a strongly anisotropic texture. Further work in this area will provide the technical specifications for a patent application. In support of this project, work has continued on the methodology development of strip-mill simulation using both the MTL Cam plastometer and the Gleeble simulator. The agreement with Dofasco contains cost-recovered activities, including the mathematical modelling of the required hot-rolling process.

Complementing the work on IF steel development, a second joint agreement was developed with Noranda, to assess the formability of galvanized steel in terms of the link between coating characteristics, in particular galvanneal structures, drawing deformation, and the coating susceptibility to powdering and



Effect of finishing temperature on the mechanical properties of interstitial-free steels HR - hot rolled, CA continuously annealed, CR - cold rolled

Finishing temperature 760°C, coiled at 600°C, 4 h



Finishing temperature 760°C, continuously annealed, 850°C, 15 s

Microstructures of titanium-niobium stabilized interstitial-free steel, warm rolled and continuously annealed. Etched in 2% nital, magnification 100 X.

flaking. Results thus far indicate that the various deformation tests yield variable degrees of cracking of the Zn layer as opposed to powdering and flaking. Weight loss, tape tests and image analysis are being compared as methods for establishing the degree of flaking resulting from drawing deformation.

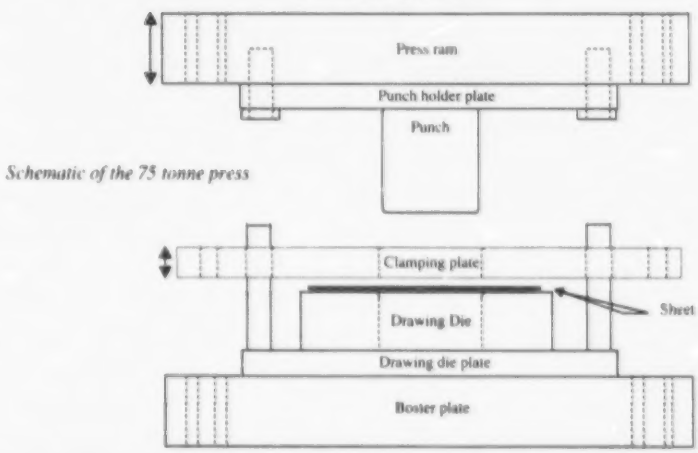
Formability Test Development

In recent years, stamping operations have become increasingly complex to meet the need for better design, reduction of cost and improvement in fuel economy. In turn this has led to an increased demand for more formable steels and for a better control of sheet metal stamping processes. The complexity of most stamping processes makes the prediction of the performance of a metal under specific conditions difficult - mainly because of the anisotropic behaviour of metals. There are a number of tests to evaluate the formability of materials in stretching, bending, plain strain deformation and deep drawing. However, most of these tests do not offer any flexibility in the control of the forming process variables. Recent research has shown the importance of studying the stamping processes as a complete system because a number of stamping variables are interconnected,and their effects should be studied by a single test.

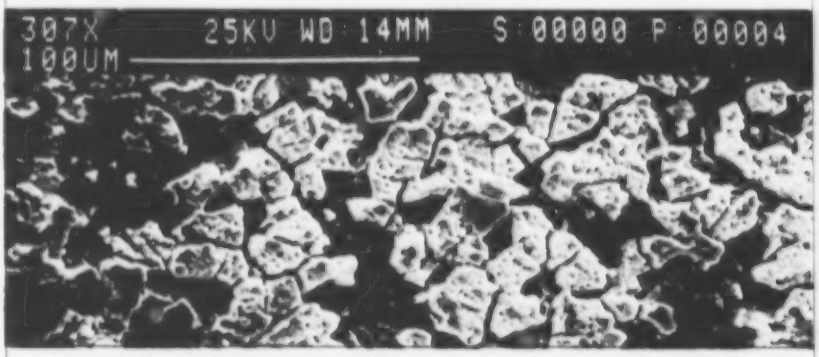
Such a universal test will provide an experimental tool for studying the process control systems of complex stamping operations. It involves the design of a universal die that allows for easy change in the process variables. The test will aid the die designer, provide data for modelling and reduce die "try out" in the stamping shop by establishing a more systematic approach to process adjustment.

Assembly work has started on a 75 tonne press, designed at MTL and dedicated to stamping operations. The hydraulic system and press frame were chosen such that the oil pans 8 x10 inches can be made or a maximum load of 75 metric tonnes can be reached. The maximum speed of the punch is 25 cm/s which is in the mid-range for industrial presses. When complete, the press will be a unique processing simulator that can be used to demonstrate the utility of the MTL universal stamping test.

Overall view of press



Schematic of the 75 tonne press



Scanning electron micrograph of a galvanneal coating after severe deformation by the double Olsen test. The double Olsen test produces significant peeling off even in a good commercial galanneal steel sheet. The bright area is the coating left on the surface after the test.

Mathematical Modelling of Hot Rolling
Achieving a targeted thickness requires a prediction of roll-separating forces so that the roll-gap setting takes into account the elastic deformation of mill components. In hot rolling the roll force is a complicated function of slab geometry, reduction rate, temperature, and mechanical properties of both the slab and rolls, as well as friction at the roll/slab interface. The relationship between rolling force and these factors is not well understood. The development of new steel grades and the computerization of process control methods has created a need for a better and more efficient method of predicting roll force.

In the past, the metal-rolling industry adopted a simplified approach which assumes that homogeneous deformation exists throughout the roll bite. Since the applicability of this approach is limited, MTL has developed a methodology, MATMOD, which incorporates a non-uniform strain distribution in the roll bite and includes both static and dynamic re-crystallization effects.

MATMOD has been applied in the prediction of rolling forces for which experimental data are available for comparison. The predicted results have been compared with both the experimental data and the results obtained by other methods and are shown to be superior to other predictive methods.

Electrical-Grade Steels to Minimise Transformer Core Losses
Transformer cores made from steel grades containing 6.5 wt% Si experience only 40% of the losses of coes manufactured from conventional steel grades. This reduction in core losses represents considerable energy savings to utility companies which eventually get passed on to the end user. However, low ductility and rapid oxidation which occur during the rolling of electrical grades of steel have to be overcome before production of these grades becomes a viable proposition in Canada. The facilities at MTL are being used to determine if there is any combination of chemistry and/or thermomechanical processing that can overcome or avoid these problems.

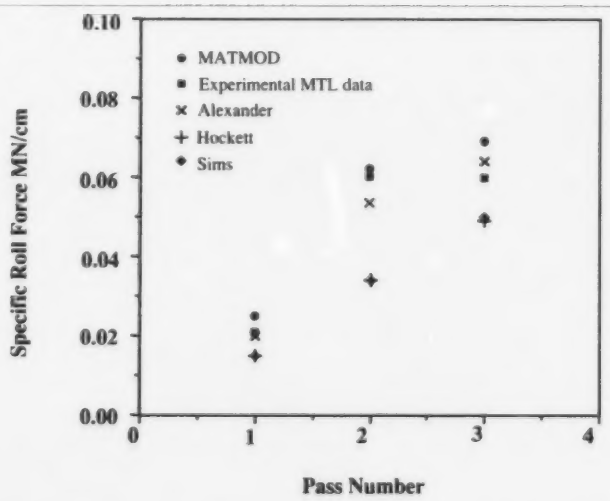
Three trial heats of electrical grade steels, viz Fe-6.5 Si, have been continuously strip cast on the casting simulator, and subsequently hot rolled to sheet. Samples are being prepared for magnetic property evaluation.

Plate Steels

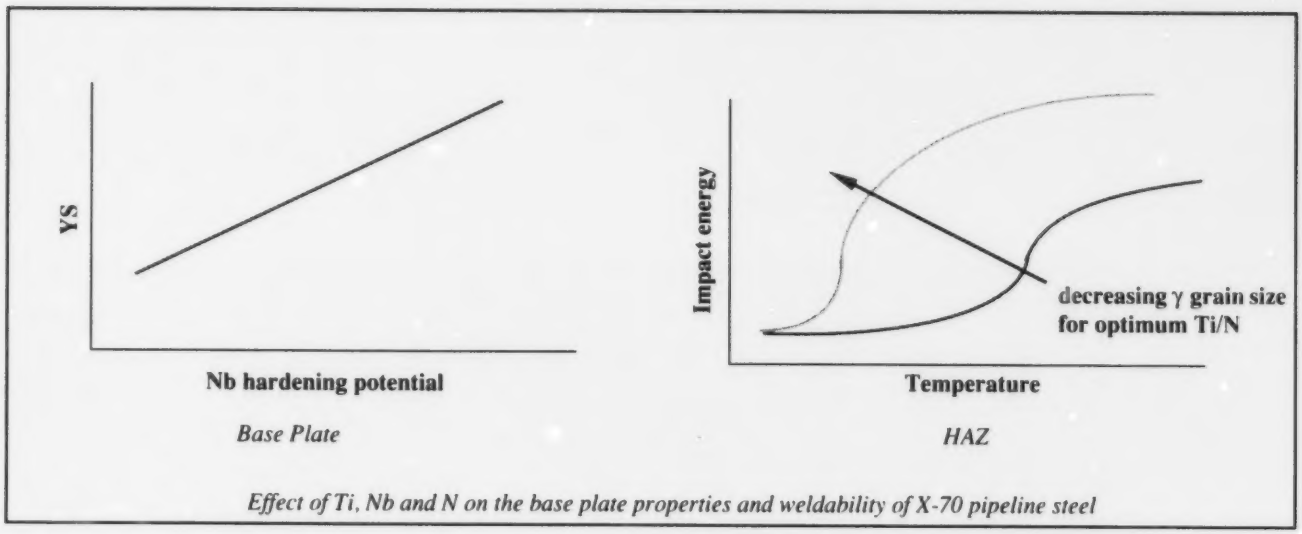
High Strength Steels for Marine Applications
There is world-wide activity to produce high strength plate (400-750 MPa yield) for hulls, offshore structures and pipelines. Conventional high-strength steels require stringent welding conditions to produce defect-free welds. The development of high-strength low-alloy (HSLA) grades with a leaner alloy content can provide cost savings by eliminating the need for preheat during welding in addition to cost reduction associated with reduced levels of elements such as Ni, Mo and Cr.

MTL is performing pilot scale work to develop new grades of steel. Its unique facilities, Gleeble 1500, pilot-scale rolling mill, dilatometer and cam plastometer can be used in the preliminary phase of high-strength steel development to identify the optimum composition and processing routes to meet given property requirements. The effect of B and Ti on the HAZ properties has been completed for HSLA80 and the effect of similar chemistry modifications on HSLA100 is underway. The goal is to develop and transfer to Canadian mills, composition and processing technology for HSLA80 and 100 weldable steel plate for marine vessels and structures.

Pipeline Steels
MTL's expertise in high-strength steels has been directed toward pipe skelp processing, and agreements were signed with Stelco and IPSCO covering several areas of mill technology. The Stelco project will get under way in 91/92, when MTL mill trials will seek to detail the metallurgy of on-line accelerated cooling in order to point to key design parameters for on-line accelerated



Comparison of MATMOD with MTL's experimental data and the models of Alexander, Hockett and Sims



Effect of Ti, Nb and N on the base plate properties and weldability of X-70 pipeline steel

cooling practice in a producing plate mill. The work on IPSCO's X70 HSLA plate has concentrated on using modelling tools and continuous cooling transformation (CCT) data to develop mill schedules designed to maximise property control in the product. MTL's coupled thermomechanical model for hot rolling will be expanded to include CCT data. The validation of the modules of processing-property modelling on MTL's pilot plant will be supported by a 300 k$ grant from an Industry Science and Technology Artificial Intelligence Fund.

In a second collaborative agreement with IPSCO, the effect of composition and processing parameters on the weldability of X80 skelp is being documented in terms of the toughness and sensitivity to hydrogen-induced cracking of the heat-affected zone. To date five of a series of ten X80 heats have been cast, rolled and base-plate properties established.

Shaped Products

The activities on forged, rolled and semi-finished steel products includes the applications of microalloy steel; exploratory work on in-house steel wire production; the direct forging of concast billet; the production of a monograph on rail steel and confidential work. The capability of producing custom lots of welding wire in-house has been advanced by commissioning a wire drawing machine, and designing a controlled-vacuum, continuous-line annealing furnace to operate in tandem with a four-die cold swager.

Microalloyed Seamless Tube

The most significant element of work on microalloy steels is that pursued in collaboration with Algoma and McGill University to produce an 80 ksi (lower yield) product for seamless tubes. The four experimental Ti-V-N steels cast at MTL were processed in four different pilot-scale controlled rolling and cooling schedules simulating the boundary capabilities of Algoma's seamless tube processing. It was shown that accelerated cooling was necessary to reach desired strength levels at the lower C and V levels, and that a combination of in-line normalising prior to finishing deformation, followed by accelerated cooling after final forming, produced a desirable combination of strength and toughness. It is believed that the normalising step confers improved toughness by reducing the carbonitride precipitation strengthening. Algoma Steel has proceeded with accelerated water-spray cooling tests directed towards plant trials of the new tubular integrated process.

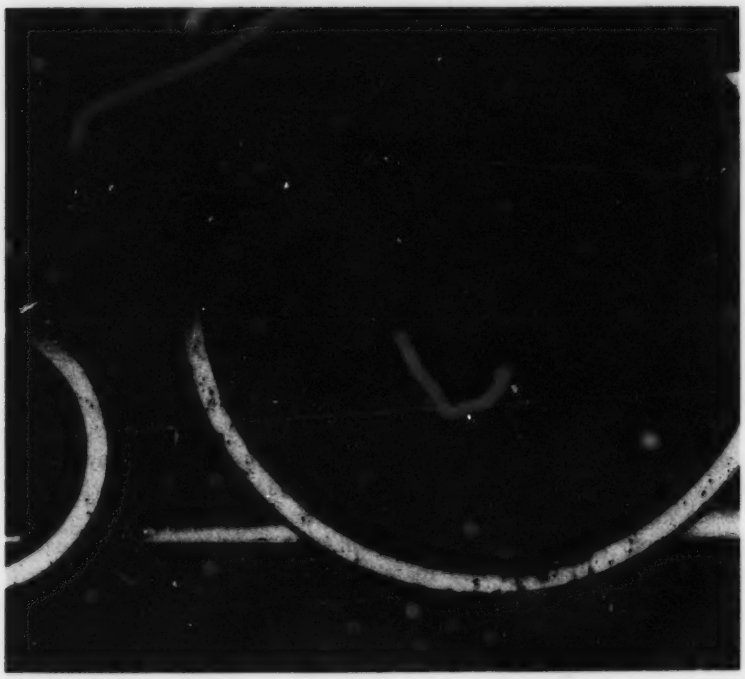
Applications for patents of the new tubular technology have been filed in Canada and the U.S., and agreements have been made with Algoma Steel for CANMET and McGill to share in royalties accrued from licensing of the technology to other producers.

Microalloy Forging Grades

A generic study on microalloy forging grades was initiated by producing three compositions of ingot, and designing pilot mill rolling schedules using cam plastometry. These schedules, both conventional controlled rolling and recrystallisation controlled rolling, will be used to simulate forging. In a further study, microalloyed 5160 grade for automotive (spring) applications has been produced with combinations of Nb and V. Again, plastometry data has detailed the rolling schedules to be performed, using derived recrystallisation and grain refinement information. It was shown that, at the high carbon level of this grade, the retardation of recrystallisation at 1000°C by alloy addition becomes more pronounced through the series 5160+Nb: 5160+V: 5160+V+Nb.

Effect of Experimental Parameters on Metallurgical Properties

Experimental parameter	YLS (MPa)	UTS (MPa)	Brinell hardness BHN	Toughness at -40°C (J)
Accelerated cooling	↑ 100	↑ 140	↑ 30	↓ 80 (low C) ↑ 20 (high C)
Increase of C	↑ 50	↑ 120	↑ 15	↓ 130
Increase of V	↑ 50	↑ 70	↑ 5	↓ 80
In-line normalizing	↑ 50	↓ 30	↓ 15	↑ 80



Rail Steel Monograph

In the fifties, sixties and seventies railways throughout North America and Europe gradually increased wagon tonnage from 30 to in some cases 125 tons which resulted in a significant increase in axle load Consequently, standard carbon rails started to show devastating signs of wear. They had to be replaced every few months, particularly on heavy duty curves, and designers were called on to improve the economic life of rails by examining harder, cleaner, more wear resistant steels as well as rail and wheel profiles.

The Metals Technology Laboratories seconded a researcher to The Rail Technology Centre in Derby, England as early as 1976 to gain expertise in rail wear. This same researcher has gone on to make a significant contribution to the body of knowledge on wear. His interest in rail steels culminated in 1990 in a monograph on "Rail and Rails Steels". The monograph is unique, aimed at the the rail engineer, it is believed to be the only up-to-date metallurgical research review covering the whole gamut of rail from processing to welding. Rails and Rail Steels details MTL's contribution to rail technology, and is undergoing final editing.

Foundry Technology

3

The foundry technology program is designed to address current problems in the foundry industry such as pollution abatement, energy utilization and product quality. At the same time MTL is developing technology designed to maintain the competitive edge of Canadian foundries.

The major thrusts of the program are

- process development for permanent moulding to reduce sand use, to automate and to increase yield
- process control of melting and moulding lines using expert systems
- reclamation of waste sand
- technology transfer by workshops and publications.

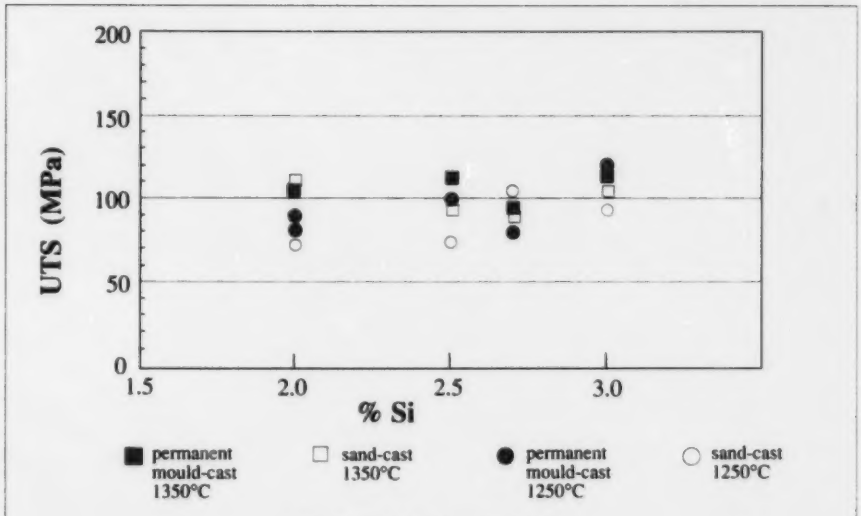
In addition, casting technology is developed to support other MTL program areas.

Foundry Process Development

Work on process development is both process and product driven. Gravity permanent mould casting, evaporative pattern casting, vacuum pouring and low pressure die casting are processes under development. Austempered ductile iron grinding balls and CANMETCOAT digger teeth are examples of products driving the work.

Gravity Permanent Mould Casting Addresses both Quality and Health Concerns

Increasing concern for the environment and working conditions, coupled with demand for better surface finish and more precise and consistent dimensional control, are making it hard for sand castings to compete with permanent mould cast parts. The future for permanent mould casting of ferrous and non-ferrous alloys especially cast iron, brass and bronze, cobalt and nickel-base alloys appears promising.



Tensile strength of ferritized plate

Microstructure of gravity permanent mould cast cast iron

Copper-Base Alloys

Demonstrations of the permanent mold casting of copper-base alloys were made to several prospective clients using MTL's IMR casting machine. Following the demonstrations, MTL and the International Copper Association entered a cost-shared agreement to machine-cast plumbing fittings. A comparative study is being carried out for an industrial client on the mechanical properties of copper-base alloys cast in both ASTM and ISO permanent test bar molds.

Four alloys, silicon brass, low-lead tin bronze, high-zinc yellow brass and low-zinc yellow brass have been cast at two different lead levels. Work on castability and gating design led to the Best Paper Award from the Brass and Bronze Division of the American Foundrymens' Society for "Some experiments on castability and gating in the permanent mould casting of copper-base alloys". Future work will focus on facilitating the permanent mould casting of low freezing range alloys such as tin bronzes and on the determination of the castability of properties of low-lead alloys for plumbing applications.

The revenue-generating work on permanent mould cast copper-base alloys will produce samples at lead levels of 0.5 and 1.0% in each of permanent and sand moulds. Castability, in terms of hot tearing resistance and fluidity, and corrosion and dezincification properties will be detailed. The experience gained in mould design will

Advantages of permanent mould iron castings

1. In sand foundries, maintaining acceptable working conditions is becoming increasingly costly. To keep dust levels low, rigorous "house cleaning" activities must be maintained, and extensive ventilation and air cleaning facilities provided. A good working environment is far easier to achieve in a permanent mould operation.

2. Sand operations are becoming more expensive. The price for dumping used sand and for sand recycling is mounting.

3. Permanent mould castings can be made with excellent surface finish. This can often eliminate machining.

4. Permanent mould iron castings have been shown to have better machinability than sand castings.

5. With modern automated machining, the dimensions of a casting must be consistent. With sand casting, this can only be achieved with very close control of the sand system and mould operations. With permanent moulds, the castings will always have consistent dimensions, without the need for sophisticated controls.

be used for a group-sponsored research proposal.

Cast Iron

The production of cast iron in "permanent" or metal moulds currently accounts for only about 3% of the total iron castings produced in Western Europe and North America. It is more popular in Eastern Europe and Russia where some 6 to 12% of iron castings are made in metal moulds. The advantages of permanent mould casting of iron which will inevitably lead to its increased use are given in the table above.

Using water-modelling and test castings, guidelines are being written on gating design for the permanent mould casting of cast iron. The problem of liquid jetting at ingates has been thoroughly documented, and appropriate pour rates and ingate designs derived. A comparison of the properties of cast iron from permanent and sand moulds showed that there is not the expected strength advantage in the more rapidly solidified product. The finer graphite flake size in permanent mould iron occurs in interdendritic colonies which effectively reduce the strength to a value equivalent to that in a sand cast iron with its larger individual flakes.

Both water-cooled (Cu and Al) and siliconised cast iron moulds will be tested with Co-base alloys and cast iron. Preliminary work on pack siliconising the cast iron mould cavity surface in a H_2/N_2 atmosphere will be further developed using thermal shock tests and trial casts to assess the performance of the modified mould surface.

Cobalt- and Nickel-Base Alloys

Development of water-cooled permanent moulds for casting cobalt and nickel alloy parts is being pursued under the terms of a joint agreement with a Canadian foundry. A copper alloy mould has been designed and built and will be tested/modified in MTL, and put into production late in 91/92. Among the expected advantages of the process are fine structures due to the fast cooling rates and absence of the carbon pick-up experienced with current resin-bonded sand moulds.

Near-Net Shape by Vacuum Pouring

Vacuum pouring has come under scrutiny recently for commercial application because of several advantages such as near-net shape, thin wall and the improved metallurgical quality expected from a reduction in reoxidation, slag entrapment, and improved mould filling control, i.e. higher effective fluidity and higher strength and ductility.

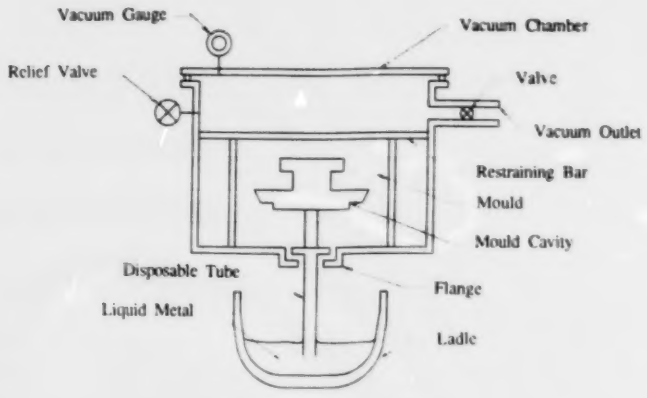
To make this advanced casting technique acceptable to Canadian foundries, MTL has developed a vacuum box to cast a variety of alloys including steel, monel, red brass and aluminum-base alloys using both green sand and CO_2-bonded sand moulds. The mould is filled by sucking metal up a hollow tube and hence oxidation of molten metal and formation of large inclusions are minimized. For control purposes, castings were also poured by the conventional gravity-casting practice in these two types of sand moulds. The increase in fluidity and decrease in mould filling time observed with vacuum poured monel and aluminum alloys will be an asset in producing thin-walled castings.

High-Strength Monels with Good Corrosion Resistance

Cast monels find many applications in the marine, offshore and petrochemical industries because of their high strength and good corrosion resistance. At present monels are imported from the USA. With MTL-developed technology and support, Canadian ingot makers would be able to prepare ingots in their own smelters. In addition, the production of premium quality castings would realize a total income in excess of $ 200 k per year.

Work on the melting and casting technology for higher strength monels and on the effect of minor alloying elements on strength, toughness and weldability, has been completed and demonstrated to an industry client.

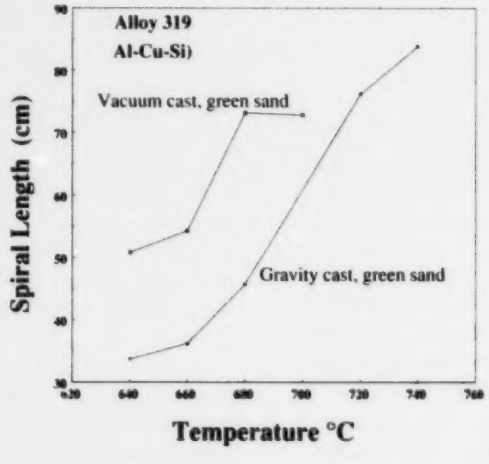
Following the establishment of the foundry characteristics, mechanical properties and weldability of monels the melting and casting technology was demonstrated at a client's foundry where



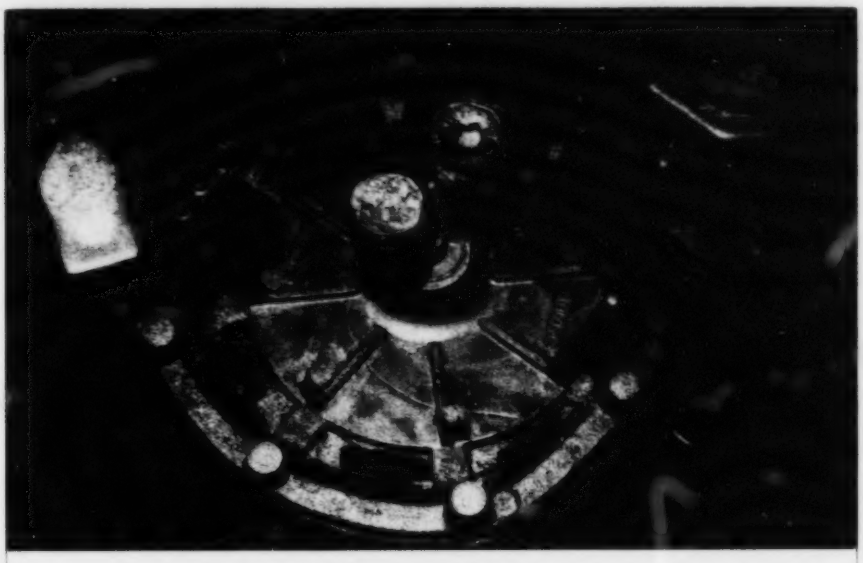
Schematic of the vacuum pouring process

Decrease in Mould Filling Time Demonstrated by Vacuum Pouring

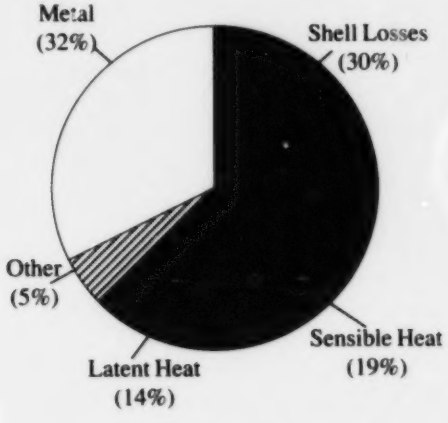
Process	Degree of Vacuum (mm)	Time (s)
Vacuum	210	1.9
Vacuum	380	2.8
Vacuum	510	3.1
Vacuum	550	3.0
Gravity	-	6.9



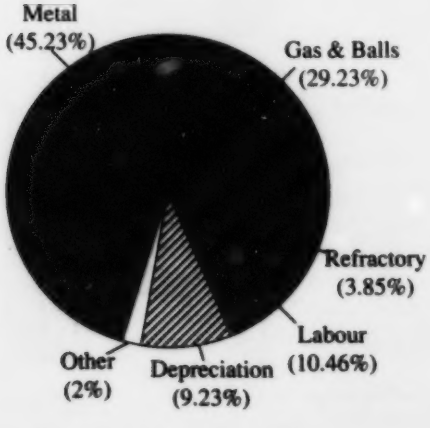
Increase in fluidity demonstrated by vacuum pouring



Monel impeller cast in a client's foundry under the supervision of MTL personnel



Energy distribution in a cokeless cupola



Breakdown of metal costs for a cokeless cupola

an impeller and a pump housing were cast under the supervision of MTL personnel. Further work on the optimization of composition for weldability is in progress with attention being focussed on C, Si and Nb contents.

Foundry Process Control

Process control is intended to assist the 250 Canadian foundries improve their products and control costs. Foundries, automotive foundries in particular, are required to use statistical quality control to build quality into their products rather than relying on inspection to establish quality after casting. Modern production methods require that castings be of consistent dimensions, with no flashing or other imperfections to confuse robots used to orient castings for subsequent machining operations. The melting, moulding and casting processes must be controlled to achieve this dimensional accuracy. Examples of the elements in this project that assist these aims are real-time control of cupola melting, real-time control of sand systems, sand testing, reclamation and control of recycled sands and workshops for foundrymen.

Real-Time Process Control for Built-In Quality

MTL has the equipment and the data-logging software to perform real-time monitoring of cupola melting to ensure control over metal chemistry and temperature. Real time process control is also carried out on green sand systems to control sand properties thereby controlling mould dimensions by reducing spring back and mould wall movement. Once the relationship between process parameters is understood the aim is to control the processes by the appropriate sensors and control mechanisms.

Using MTL-developed software for coke fired cupola management, a series of field trials was conducted on a gas-fired cupola in a collaborating foundry, and a computer-based expert system was derived to predict metal and slag chemistry, melting and combustion efficiencies, and total metal costs at the furnace spout.

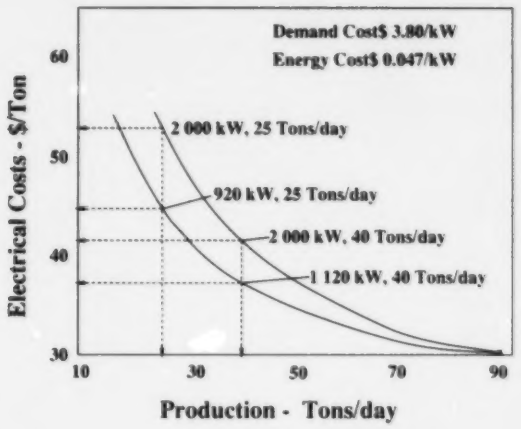
Energy Savings Using Electric Furnace Management Software

MTL's electric furnace management software, transferred to Ontario Hydro seven years ago, was used to perform melting energy studies at three Ontario foundries. The total number of foundries thus serviced is now sixteen. From the database generated, a cost envelope approach may yield savings between $1 and $25 per ton depending on site-specific parameters. In addition to these programmable operational savings, it was shown that shifting the heavy power demand of a large channel furnace, for example, away from the demand peak of the rest of the plant can give the melting department free demand, in a form of localized 'off-peak' melting, as a result of reduced demand charges.

Sand Reclamation Demonstrates Environmental Awareness

The cost of disposal of waste foundry sands ranges from $65/ton in Montreal to $95/ton in the Toronto area. Disposal costs continue to increase with little relief in sight, either in the form of approved landfill or alternate uses, such as road bed filler. Sand reclamation technology is therefore of great interest, and in collaboration with the Canadian Foundry Association, MTL has issued a report evaluating European and Japanese reclamation plants. In addition, MTL has contracted with AISCO Ltd. to perform a techno-economic analysis of a green-field reclamation plant in the Quebec-Windsor corridor. A spread sheet analysis will enable interested parties to establish a return on investment as a function of site, throughput, etc. This project, and the CFA-MTL evaluation of reclamation technology, was presented at the annual CFA meeting in June 1991.

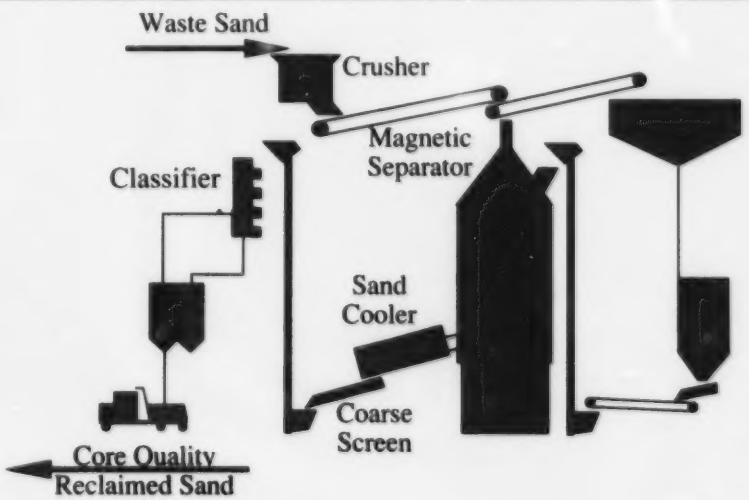
The problem of sand disposal will continue to be addressed by pursuing work already started with Environment Canada and the Ontario Department of the Environment. In both instances, MTL's role will be to supply the technical back-up to ensure that data generated and standard waste sand leaching test methods recommended are well-founded from both the producers' and regulatory perspectives.



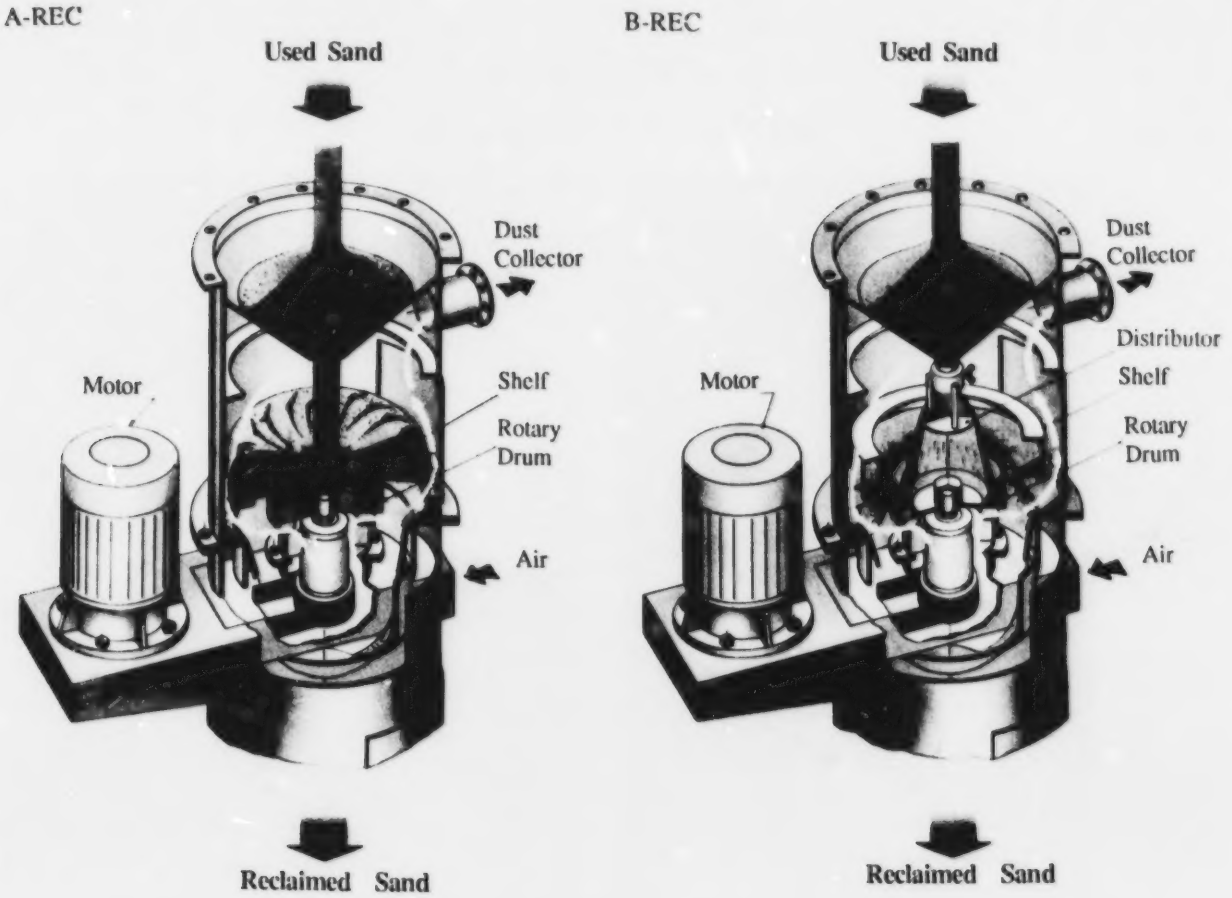
Electrical costs for melting cast iron in an electric induction furnace

Cost Analysis Carried Out as Part of an MTL-AISCO Systems Engineering Study To Investigate the Feasibility of Installing a Sand Reclamation Plant in the Quebec-Windsor Corridor

- 12 tph laundry $ 9.9 million
- 6 tph laundry $ 6.9 million
- 3 tph captive plant $ 5.0 million
- Microeconomic model for plant
  - user selects foundries
  - user selects plant location
  - model selects plant and equipment
  - model selects depreciation
  - user selects interest rate
  - model predicts costs, cash flow, etc.



Schematic of a sand reclaimer

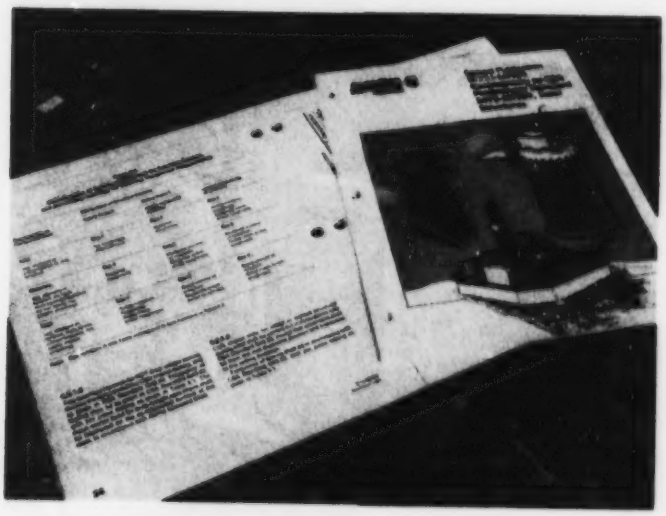


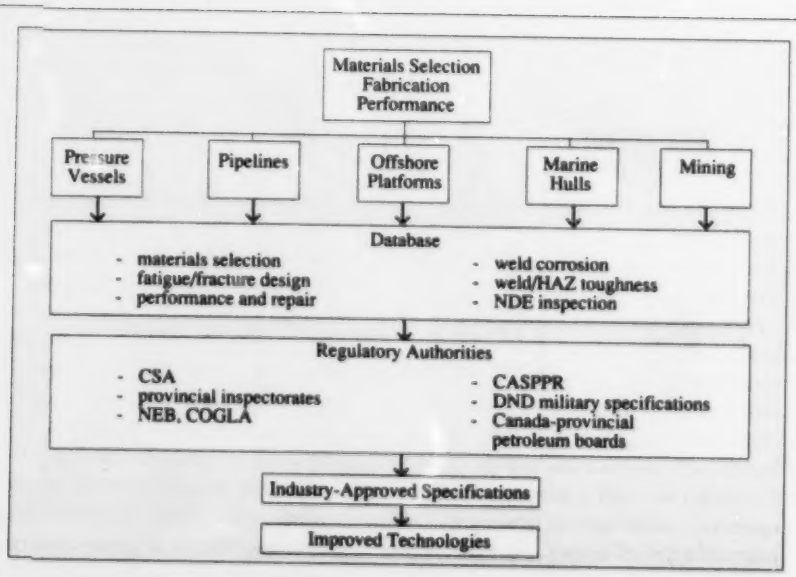
Japanese rotary sand reclaimer

It is hoped that the output of the design work on a sand reclamation plant will lead to a joint industry-government initiative in establishing a pilot treatment plant, perhaps in a host foundry, to assess reclamation operations on Canadian sands. In support of this target, consideration is currently being given to setting up a bench-scale reclamation line in CANMET to bracket tonnage plant operating conditions for treating a range of types of binder.

Technology Transfer through Non-Ferrous Casting Workshops

As part of a technology transfer program in support of the Canadian non-ferrous foundries, workshops on "Non-Ferrous Casting Technology" were organized in Edmonton, Alberta; Vancouver, B.C. and Oakville, Ontario in English and at St. Hyacinthe, Quebec in French. Various topics covered were melting of copper and aluminum-base alloys and zinc-aluminum alloys, gating and risering of non-ferrous castings, control of green sand and reclamation of foundry sand, and environmental issues. In addition, highlights of MTL's current foundry research activities on permanent mould casting, low-pressure die casting, vacuum casting and filtration were presented. The total attendance in these four places was 94. The local chapters of the American Foundrymen's Society provided assistance in the organization of the workshops in Edmonton, Vancouver and St. Hyacinthe; whereas the Non-Ferrous Founders' Society, Canadian Management Group and the Canadian Copper and Brass Development Association organized the one in Oakville.




Materials Selection
Fabrication
Performance
Pressure Vessels
Pipelines
Offshore Platforms
Marine Hulls
Mining
Database
- materials selection
- fatigue/fracture design
- performance and repair
- weld corrosion
- weld/HAZ toughness
- NDE inspection
Regulatory Authorities
- CSA
- provincial inspectorates
- NEB, COGLA
- CASPPR
- DND military specifications
- Canada-provincial petroleum boards
Industry-Approved Specifications
Improved Technologies

Materials for Resource Industries

Prevention of catastrophic failure of alloys and systems subject to aggressive environments is crucial to environmental protection. Historically, materials selection, which is critical to structural integrity, has been based on previous experience. Failure to properly select the correct material for a specific purpose will often result in failures which have a far reaching impact on the environment. Mechanical property data exist for a wide range of commercially-available alloys. However, correlations between the operating environment and materials properties rarely exist, and engineering judgement regarding life prediction must be used under severe environments such as those in the Canadian Arctic. MTL research is aimed at making materials selection and life estimation a scientific process that bases failure prediction on quantitative assesssment methods and statistical methodology as well as sound engineering judgement. The Materials for Resource Industries Program serves a wide client base in the petroleum, mining, pulp and paper, resource transportation, and shipbuilding industries. It addresses safety, environmental and productivity issues by recommending the safe and economical application of metal products.

Protection Technology to Safeguard Health and the Environment through Materials Selection for Offshore Structures

Wave conditions encountered on Canada's East Coast are similar and in some cases more severe than those encountered in the North Sea. Hence, oil and gas exploration and production systems that utilize steel structures containing welded tubular joints must be designed against fatigue.

Fatigue of Welded and Tubular Plate Joints

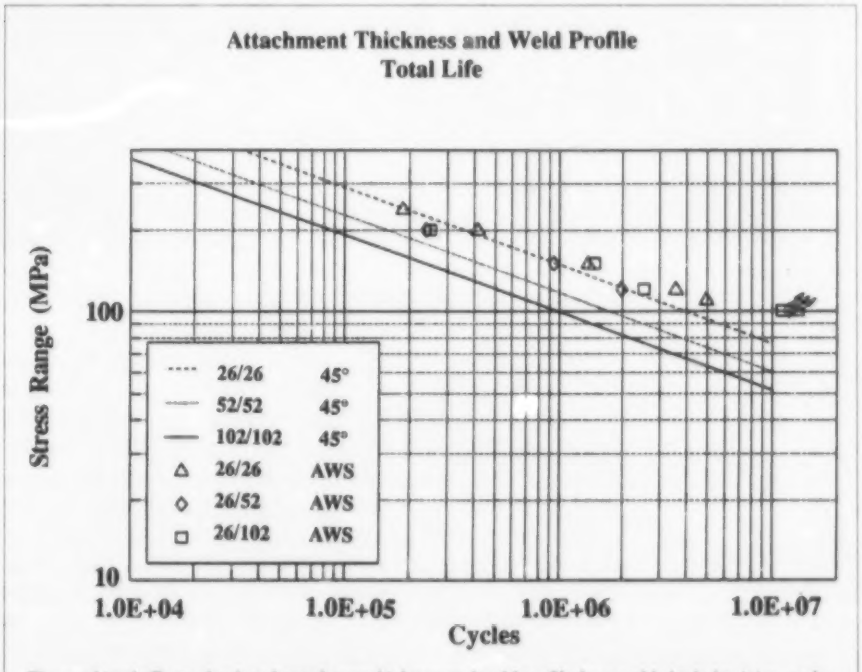
A significant milestone was achieved in MTL's fatigue and fracture program with the publication of the CSA Standard S473 for Fixed Offshore Structures in late 1990. On-going fatigue research is showing that the fatigue specifications can be improved with respect to the treatment of combined loading and thickness effects.

The design life of a tubular is considered to end when a fatigue crack penetrates the chord wall of a tubular joint. In single-mode loaded joints the crack has spread around one quarter of the brace circumference at the time of wall penetration and the residual life of the "failed" joint can still be up to an additional 70% of the original design life. As anticipated, when tubular joints were fatigue loaded in axial and out-of-plane bending modes, cracks developed at three locations which combined into one crack almost three quarters of the brace circumference long at the time of wall penetration. As a result the residual life was negligible which left very little safety margin. In theory, the design curves based on single-mode crack testing leave a large safety margin; in reality, under conditions of combined loading, the residual life of a tubular is very much reduced after wall penetration.

The adverse effect of increasing thickness on fatigue life, incorporated in fatigue design codes, was measured on welded joints with scaled-up attachment and base-plate thicknesses. However, the majority of welded joints have attachments thinner than the base plate. The thickness effect in these joints may be smaller than that based on the assumption of equal thickness. The American Welding Society (AWS) Code for Offshore Structures assumes that the adverse effect of increasing base-plate thickness can be mitigated by improving the weld profile.

An experimental program designed to evaluate and quantify thickness effect in joints with thinner attachments, with standard or improved rounded profile of the weld fillet, has been completed. Plate welded joints with section thicknesses from 26 to 102 mm were used. The results show a significant reduction in thickness effect when the attachment thickness is kept constant and only the base-plate thickness increases. Further alleviation of thickness effect is is obtained using improved weld profile, particularly on thick sections. After final analysis the results will be used to revise the clause on thickness effect in the CSA Offshore Structures Standard.

Current design curves, developed and used for North Sea applications, are based on the results of fatigue tests of small-scale specimens and larger tubular joints

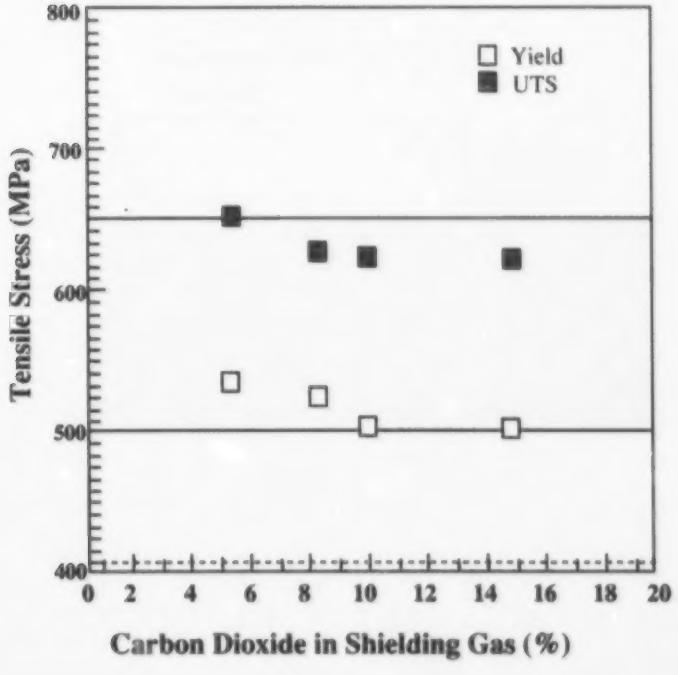


The combined effects of reduced attachment thickness and weld profile for a welded tubular joint can be seen in the fatigue curve above. An increase in thickness from 26 to 102 mm reduces the fatigue life by a factor of over four. If the attachment thickness is kept constant at 26 mm, the increase in the base-plate thickness only reduces the thickness effect to about a factor of two. A similar reduction in thickness effect is observed on joints with equal attachment and base-plate thickness after using the improved AWS weld profile instead of the straight 45° fillet. The thickness effect almost disappears when a constant attachment thickness (26 mm) is combined with an improved weld profile.

without stiffeners. However, the majority of tubular joints in service contain internal stiffeners which alter the stress distributions in a joint. Fatigue bending tests of wide plates with long cracks, with and without welded attachments have shown that, at crack depths approaching one half the plate thickness, surface crack growth rates start to control in-depth crack growth. Factors influencing the crack surface-growth behaviour were found to be the longitudinal weld-toe stress distribution, the nominal ligament stress ahead of the crack and the weld-toe stress history. The results to date indicate that, by retarding surface growth through the use of properly-spaced stiffeners, significant fatigue performance improvements may be realized. Two welded tubular joints with optimized stiffener details are being prepared for testing and subsequent analysis. The long term objectives are to develop design rules and analysis software for a wide variety of stiffened welded structures.

Charpy Toughness at -30°C of ER480-S6 Weld Deposits as a Function of the Carbon Dioxide Content of the Shielding Gas

CO_2 Content %	Test Results J					Average J
5	65	85	86	97	107	89
8	55	60	71	82	91	71
10	66	76	80	80	96	79
15	66	72	77	82	86	77



Yield strength and ultimate tensile strength as a function of the percentage of carbon dioxide in shielding gas for ER480-S6 wire

Fracture of Welded and Tubular Plate Joints

Structural integrity is also under investigation from a fracture viewpoint. Work is concentrated on establishing the significance of local brittle zones in the heat-affected zones (HAZs) of welded joints of large engineering structures. It is hoped to demonstrate the likelihood of brittle fracture initiation as a result of interaction between a flaw and a local brittle zone is small, which will enable the relaxation of conservatism in design codes. A statistical model has been developed to describe the probability of fracture initiation in an HAZ. The crack-tip opening displacement (CTOD) toughness at -30°C has been measured as a function of the proportion of grain-coarsened HAZ. Bending-type wide-plate test specimens have been fabricated with a full-width surface notch placed in a straight-sided HAZ. The location and sizes of grain coarsened (GC) HAZ material below the notch along the crack plane have been measured. The information on GCHAZ locations and the CTOD as a function of the proportion of GCHAZ sampled have been used in the statistical model to predict the probability of failure. The wide-plate specimen will be tested in bending fatigue to check the model predictions against full-scale behaviour.

Progress has been made in the areas of of toughness of shielded-metal-arc and gas-metal-arc weld metal. In work on the effects of argon-carbon dioxide mixtures on the properties of ER480-S6

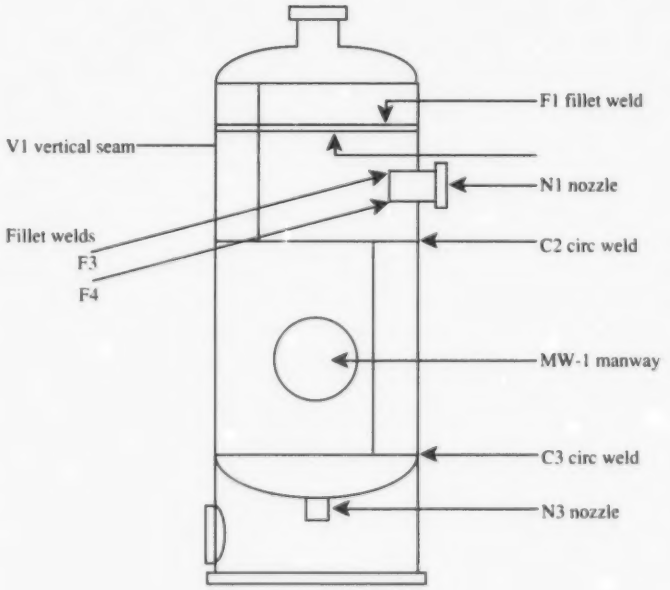
weldments that the ultimate tensile strength (UTS) diminished as the volume percentage of carbon dioxide in the mixture was reduced. This led to the hypothesis that a minimal amount of re-oxidation of alloy components is necessary to provide the nucleation of the acicular ferrite microstructure required for the optimum combinations of strength and toughness. The available de-oxidant levels of manganese and sulphur must be properly balanced with the oxidation potential of the shielding gas. The results suggest that the certification process for gas-metal-arc wire as written in W48.4 (the wire is certified as a 100% carbon dioxide mixture) could lead in more dilute argon-carbon dioxide gases, to weld deposits that have properties below those established in the certification of that particular wire. An industry cost-shared project has been set up to look at the problem in detail and provide data to rectify the present version of W48.4 and to establish a methodology by which the oxygen potential of shielding gases and de-oxidant levels in wires are properly balanced.

Technology for Fabrication, Inspection and Repair of Pressure Vessels to Reduce Costs and Improve Safety

Technologies associated with the fabrication, inspection and repair of high temperature pressure vessels have been identified for development by fabricators and the petrochemical and utility industries. Specific techniques for the joining and surfacing of thick-section steels are being developed by in-house and contract research activities in the area of fabrication. Cooperative programs with petrochemical and utility plant operators are planned with such initiatives as: demonstrating the application of engineering critical assessment (ECA) as a decision-making process for the necessity and timing of pressure vessel repair; the development of weld-repair procedures using the temper bead approach; the assessment and repair of hydrogen-induced cracking in pressure vessel materials; and improved non-destructive inspection of service-damaged pressure vessel material.

Comparison of the Fracture Mechanics Failure Pressure Prediction of a Service Damaged Heavy-Wall Pressure Vessel with the Actual Failure Pressure Measured during a Burst Test

Flaw	Level 1 MPa	Level 2 MPa	Actual MPa
Demister ring flaws	8.0	18.6	
Weld C3 - Circumferential flaw	5.1	9.0	
Weld V1 - Circumferential flaw	7.8	10.7	
Splitter plate axial flaw	9.8	11.0	16.4
Manway flaw	6.7	7.0	



Weld identification	Weld type	Number of cracks	Measured length min-max (in.)
F1	Fillet	13	00.750-69.000
F2	Fillet	12	01.000-59.000
V1	Vertical seam	3	00.125-00.375
F3/F4	Attachment (fillet)	4	Not recorded
C3	Circumferential seam	5	00.250-01.000
N3	Nozzle	6	00.250-00.500
MW1	Manway nozzle	12	00.250-02.000

Notes: V1: These cracks are reported as being in the intersection of the vertical seam and the circumferential seam C2
C3: Two of the five cracks are reported as being transverse.

Cross-section of the service-damaged heavy-wall pressure vessel burst test to failure to validate engineering critical assessment methodology.

Fabrication of Heavy-Wall Reactor Vessels

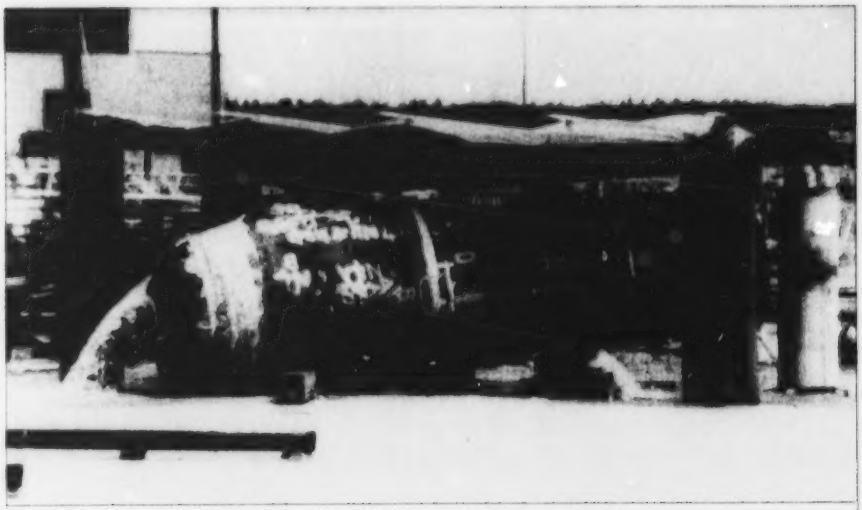
Contract work has focused on the development and assessment of stainless steel cladding technology for heavy-wall reactor vessels used for petrochemical refining. A number of two-layer stainless steel overlays were successfully produced using electroslag and submerged-arc strip welding. Both processes were able to produce acceptable overlays, but the the submerged-arc strip process was the superior operational fabrication process. The resistance of the overlay to hydrogen-induced disbonding was shown in autoclave tests to be related to the proportion of ferrite observed at the fusion boundaries.

Engineering Critical Assessment Facilitates Good Decision Making

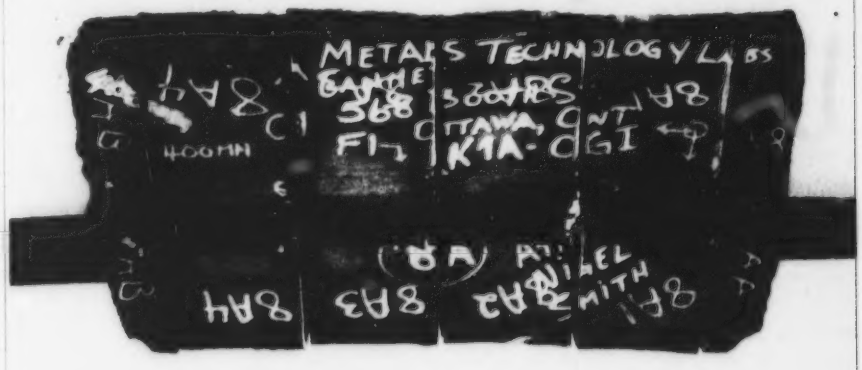
Avoidance of costly shut downs for repair can save up to $ 1 million/day for pressure vessel operators. Engineering critical assessment methods enable decisions to be made about the need to repair or replace service-damaged vessels. A consortium of thirteen petrochemical and electric utility industrial partners, as well as provincial regulatory authorities, has been formed to demonstrate the validity of ECA methods. The principle tasks involved in correlating the results from an experimental program on a service-damaged C-Mn pressure vessel with the fracture mechanics failure prediction have been completed.

Manual and automated ultrasonic methods were compared in the vessel defect assessment stage. Two of the manual methods and one automated technique reported conservative results, i.e. defects twice their actual size, determined by sectioning of the vessel. The automated ultrasonic method based on time-of-flight diffraction from the tip of a defect provided measurements in close agreement with the actual defect dimensions.

The fracture mechanics predictions of failure pressure at the various flawed sections of the vessel used measured defect sizes, an assessment of operating vessel stresses, and the crack tip opening displacement fracture toughness values



View of the service-damaged vessel following failure



Sample removed from the vessel for post-failure analysis

General view of the vessel after the burst test and sample removal

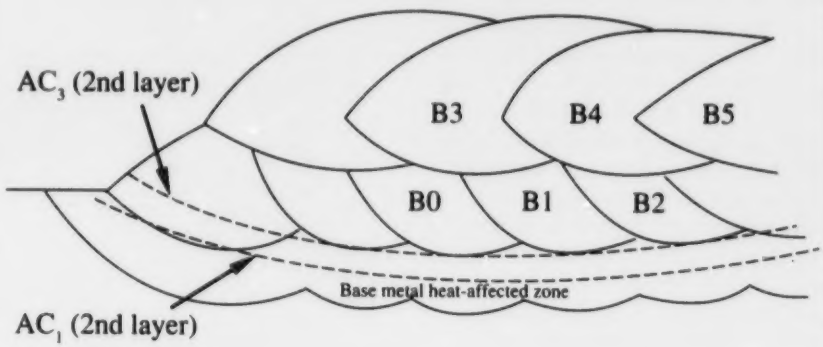
of the vessel. A burst test was used to confirm the failure predictions. During the burst test the vessel failed at the splitter plate axial flaw at a pressure of 16.4 MPa which was about 40% above that predicted, showing that the the predictive methodology was conservative.

Repair Welding to Minimize Degradation of Properties in the Repair-Weld HAZ

Temper-bead repair of service-damaged Cr-Mo vessels was investigated in a collaborative project aimed at defining a repair procedure that would minimize degradation of toughness and creep resistance in the repair weld HAZ. Gleeble simulations of first-layer HAZ response to tempering by the deposition of a second weld layer were used to predict second-cycle peak temperatures to produce minimum grain-coarsened HAZ hardness. For 2.25Cr-1Mo steel the temper peak was 770°C, and for 1.25Cr-0.5Mo it was 850°C. Actual two-layer weld repairs on these steels was performed using the simulation data to adjust heat-input ratios between the first and second passes. Excellent agreement was obtained between the predicted HAZ hardness values and those obtained in the actual weld repair.

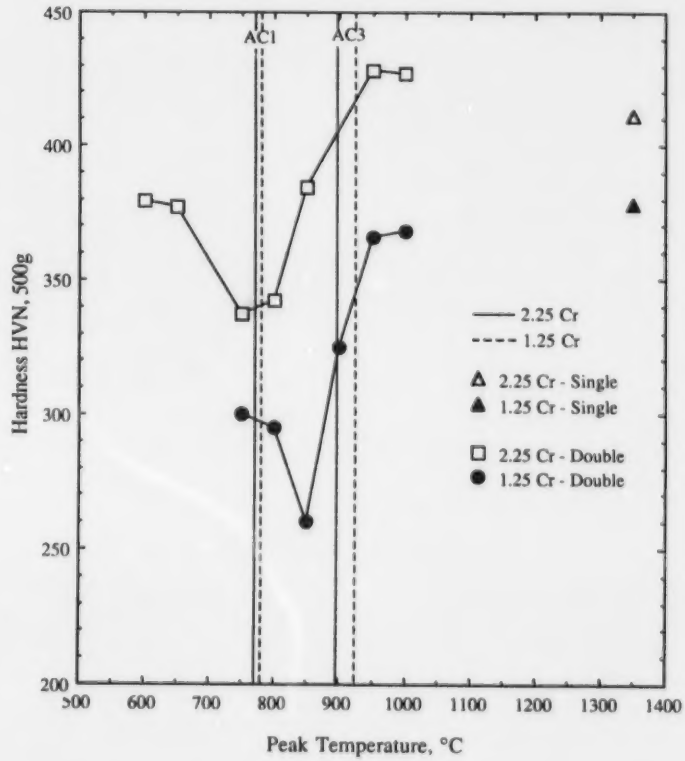
Resistance of Pressure-Vessel Steels to Hydrogen-Induced and Sulphide-Stress Cracking to Estimate Residual Life

Work has been initiated to assess the resistance of C-Mn and alloy pressure vessel steels to hydrogen-induced and sulphide-stress cracking. NACE TM-01-77 and TM-02-84 test media are being used on A516 and two Cr-Mo steels, the samples being in the form of weld-repair test coupons. The stress corrosion cracking tests on A516 conducted thus far have revealed some base-plate cracking in the plate-rolling direction after exposure to TM-01-77.



Energy input ratio 1.8

Example of a two-layer temper bead weld repair. The second layer produces intercritical reheating of the first layer coarse-grained heat-affected zone. B indicates the order in which the weld beads were laid down.



Double cycle weld repair simulation in Cr-Mo steels

Pipeline Technology to Maximise Reliability

Canada has a 10 billion dollar investment in 154 000 km of natural gas pipelines and 27 500 km of pipeline for oil and petroleum products. Many of these pipelines have been in service for more than 25 years so replacement of many lengths of line can be anticipated during the next decade. The replacement cost of the entire Canadian pipeline system is about $100 million. MTL is developing technology to improve the reliability of pipelines by addressing problems of stress corrosion cracking, sulphide stress cracking, hydrogen-induced cracking, localized corrosion and assessment of residual stresses. Improved reliability will ensure the security of energy supply and economic stability of the oil and gas industry.

Materials Selection for Future Pipelines

A major challenge faced by the steel industry is to produce a high-strength steel with a yield strength greater than 110 ksi with good resistance to sulphide stress cracking (SSC). By alloying a clean steel (0.004% sulphur, 0.004% phosphorus) with 0.001 to 0.002% boron, the threshold stress for SSC was increased from 52 ksi (45% of yield) to 81 ksi (70% of yield) for a steel of yield strength 115 ksi. To obtain a further improvement in strength, trial heats of steel with additions of niobium as well as boron have been prepared at MTL.

Growth Rate of Stress Corrosion Cracks

Because stress corrosion cracking has been discovered in Canadian pipelines, it is important to establish reliable inspection schedules and procedures to safely extend the lifetime of pipelines containing these cracks. The economic implications of life extension are substantial, so it is important to define the remaining lifetime resulting from current and future crack growth accurately.

A major joint project in this area of environmental degradation has been the commissioning of a test facility to determine the growth rate of stress corrosion cracks occurring on the uncoated outside surface of the pipe or under disbonded outer coating. MTL is conducting a one-year test on a full-size linepipe with natural and artificial cracks. The test pipe section was one that has been exposed to seventeen years service. After removal from service, it was prepared by enclosing artificial cracks in a variety of different soil, pH, bacterial and electrolyte environments thus affording varying levels of cathodic protection. It has been subjected to a pressure spectrum simulating an actual pipeline pressure history. The growth rate of the 112 artificial cracks is monitored by a DC potential drop technique. Bacterial presence and the pH of the solutions above the cracks are measured periodically. The electrochemical potentials on the pipe surface near the cracks are monitored using Luggin capillaries. After six months, no growth was detected on any crack, but after eleven months some crack development has been indicated.

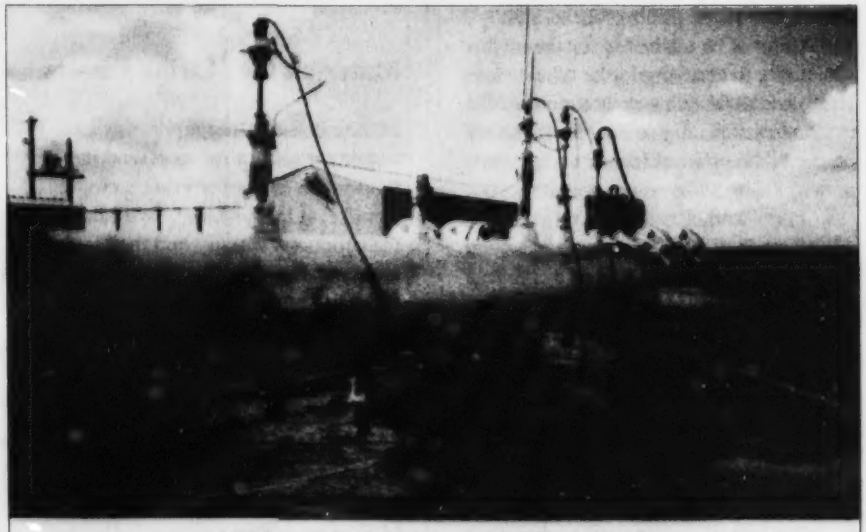
Overall view of a pipe test facility commissioned to determine the degree of stress corrosion cracking due to environmental degradation.

Inhibition of General and Pitting Corrosion

The inhibition of general and pitting corrosion in pipelines progressed from laboratory bench testing to field trials in a Mobil test loop where two inhibitors were tested. Both inhibitors reduced general corrosion, but one was superior in pitting prevention. The AC impedance measurements used were subsequently applied to monitoring in situ corrosion rates at a Nova Husky test facility. The results are being compared with data obtained by weight loss and potentiodyne techniques.

Laboratory Hydrogen-Induced Cracking Simulation to Reduce the High Costs of Field Trials

The Sour Service Task Force of the Canadian Standards Association has a mandate to create standards for linepipe steels for oil and gas transportation from wells containing hydrogen sulphide. Field trials are expensive so it was decided to assess the feasibility of using laboratory testing to simulate hydrogen-induced cracking (HIC) in operational pipelines. Because the Metals Technology Laboratories have substantial experience in measuring the resistance of steel to HIC, they were asked to conduct laboratory and field measurements to determine the concentration of hydrogen,



A test loop used in field trials to test the effectiveness of inhibitors in preventing general pitting and corrosion.

and the degree of HIC, in the wall of a new sour service grade of linepipe steel.

A loop of this linepipe steel was installed at a sour well head in Foxcreek, Alberta for the field trials. MTL evaluated the resistance of samples of the steel to hydrogen-induced cracking in the laboratory by a four-stage process which involved immersing the samples in various corrosive test solutions. The technologist who evaluated the laboratory samples spent three weeks on site in Fox Creek measuring hydrogen permeation through the wall of the pipe loop using two experimental probes, one liquid and one solid state. In one of the three runs performed on site, a corrosion inhibitor was used, cutting the hydrogen concentration on the inside pipe wall by 88%. However, the most significant finding was that the CSA test solution simulated field conditions very closely. On the basis of this comparative testing, MTL can recommend procedures for simulation of HIC in pipelines. The significance of finding the "right" steel is put into context by the market for sour service linepipe which is 660 million dollars annually in North America (60 million in Canada).

Hydrogen Cold-Cracking of Girth Welds

The group-sponsored project on the hydrogen cold-cracking of pipeline girth welds will attempt to refine predictive methodology to avoid delayed HAZ cracking. A large number of commercial and experimental steels of Grades X70 and X80 will be evaluated for their sensitivity to cracking in the reheated HAZ, and detailed computational weld mechanics and full-scale weld trials will be used in support of laboratory evaluations.

Assessment of the Reference Stress Method

Methods of engineering critical assessment (ECA) in the current CSA pipeline standards have certain limitations. In particular, because there is no explicit inclusion of plastic collapse in the method, a separate analysis for collapse is necessary.

Stemming from the increased interest of pipeline companies in more sophisti-

cated fracture control, a joint agreement has been reached to assess the use of the reference stress method in constructing a fracture avoidance diagram. The relevant physical testing of specimens is underway and will be followed by the necessary numerical analyses using finite element software. This software is newly acquired and will feature prominently in stress analysis work.

In related work, a study has been completed of three experimental, one numerical and one analytical method for measuring residual stresses in structural components. This study led to the development of new software for the determination of residual stresses.

Materials for Marine Vessels

Marine construction represents an important market for steel, and the fabrication of marine vessels employs a significant labour force. In addition to the economic activity and the employment generated in shipyards and by suppliers of steel and welding consumables, there is a clear need for metallurgical knowledge to ensure the avoidance of brittle fracture and extensive corrosion that is required for the safety of vessels operating in Canada's harsh marine environment.

MTL is performing research directed towards the weldability of high-strength steels (550-700 MPa), aspects of fracture control in marine hulls, and weld-zone corrosion. The work is being done in collaboration or cooperation with steel producers, marine fabricators, and regulatory/defence authorities. The broad objectives are to improve the competitiveness of Canadian industry, and to ensure the safe and economical selection of materials for marine vessels.

Welding Consumables and Procedures for High-Strength Steels

The evaluation of commercially-available HSLA80 and HY80 submerged-arc-weld electrodes was performed at heat inputs of 1, 2, 3 and 4 kJ/mm. With increased energy input, the yield strengths of both compositions of weld metal decreased, the effect being more marked for HY80. The high proportion of acicular ferrite in the HSLA weldments gave superior notch toughness compared with the bainitic-martensitic microstructures in HY80 welds. The effects of multi-pass welding and post-weld heat treatment on weldment properties were simulated on a Gleeble machine. The results indicate that the HY grade softens while the HSLA grade precipitation hardens after secondary heating. Estimates of the effects of heat input on weld-metal notch toughness are being made.

Two commercial HSLA steels were examined to document the factors

controlling the fracture toughness of the grain-coarsened HAZ in both Gleeble-simulated and actual weld microstructures. Although both steels exhibited a marked decrease in toughness in the HAZ with increased heat input, higher proportions of low-carbon martensite in the HSLA grades conferred better Charpy and dynamic tear properties. A series of experimental compositions derived from the better of the two commercial HSLA80 grades has been cast and rolled for weldability assessment. Preliminary results have shown that the MTL variant containing both Ti and B has superior HAZ toughness at 2 kJ/mm (149 J at -40°C) associated with a high volume percent of low-carbon martensite in the grain-coarsened HAZ.

Intermediate and Impact Strain Rate and Wide Plate Testing

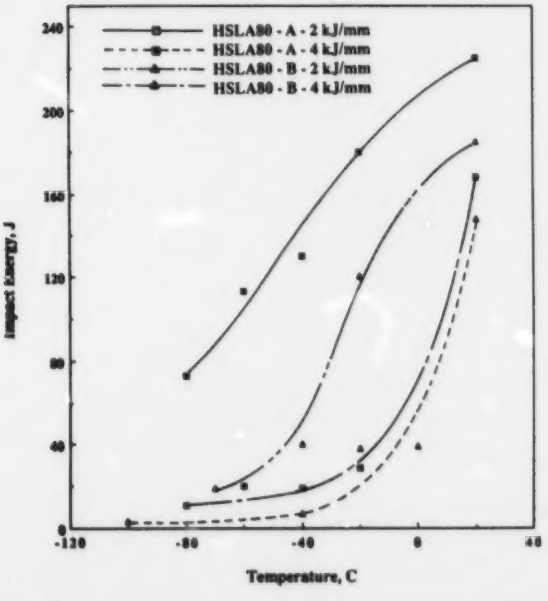
In close collaboration with the Canadian Coast Guard, MTL has begun work on initiation and arrest toughness of candidate hull steels at intermediate and impact strain rates. Welded panels have been fabricated for both small-scale and wide-plate tests. In related work, a study of toughness variability in structural steel is being undertaken in cooperation with the Algoma Steel Corporation.

Weld-Zone Corrosion

Work on weld-zone corrosion enables the wise selection of materials and welding procedures to avoid costly repairs during service life and to minimize the risk of fracture for ships in arctic service.

Composition of Two Commercial Steels HSLA80A/HSLA80B

Base metal	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Nb
HSLA 80-A	0.06	0.50	0.27	0.004	0.007	0.92	0.66	0.25	1.02	0.044
HSLA 80-B	0.03	0.40	0.24	0.012	0.008	0.80	0.70	0.22	1.18	0.040



Impact energy versus temperature for the two commercial steels, HSLA80A /B

The CANMET weld-zone corrosion tank-test facilities were engaged in testing TMCP plate; gas-metal-arc welded plates; and aluminum-metallized plates. Tank data are complemented by anodic dissolution tests on full-thickness welds, and a Hymarc laser scanner. has been comissioned to improve productivity in gathering of corrosion data. The results of the CANMET weld-zone corrosion program have been applied to the Canadian Coast Guard icebreaker Louis St. Laurent in the course of an extensive refit. Its new bow was fabricated from an Algoma EH36 plate containing <1.25% Mn as recommended by MTL, and over 3200 linear feet of weldments were capped by a tank-tested submerged-arc-welded electrode.

Currently Alcan and CANMET are working in partnership to explore the use of metallizing treatments to protect steels in Arctic waters. Both aluminum (1350) and DURALCAN 90/10, an aluminum-based composite, have been examined as coating materials. Coatings 0.25 to 0.40 mm in thickness are deposited by conventional flame or arc spraying processes by Alcan onto steel test plates containing a sample weld. The materials are then subjected to a simulated Arctic corrosion/abrasion test in the MTL tank testing facility. After a six-month immersion with no protective coating, the plates show evidence of general corrosion attack in the base metal and strong corrosive attack of either the weld metal or the heat-affected zone, depending on the composition of the weld metal and the heat input in the welding process. In samples on which a strip of 1350 aluminum was deposited over the weld and adjacent regions of the base plate, the exposed base plate showed little evidence of corrosive attack, a consequence of the cathodic protection provided by the aluminum. Both 1350 aluminum and DURALCAN provided protection for the weld metal and heat-affected zone, although the aluminum coating did experience abrasive wear. Still further improvements were observed in plates coated with the composite material. Again the aluminum composite served to cathodically protect the exposed steel base plate. The composite material also proved to be remarkably resistant to abrasion. Marks

penned onto the surface of the coating were still evident after four months of exposure, providing testimony to the durability of the composite coating.

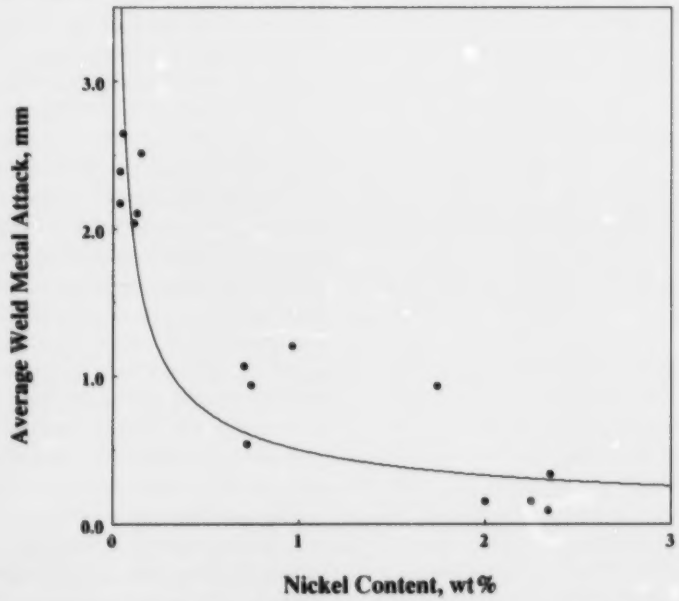
Materials for the Mining and Minerals Industry

The overall objective of this project is to improve safety, reliability and productivity by minimizing corrosion and wear.

Data on problems associated with hardfacing were collected from over one hundred mines to compile a handbook intended to assist maintenance engineers. The Pulp and Paper Research Institute assisted with the guide book which deals with the selection of hardfacing processes, consumables and procedures for rebuilding worn surfaces of components.

Austempered ductile iron (ADI) grinding balls, cast using MTL's IMR permanent mould machine, have been wear tested in a US Bureau of Mines mill simulator, and a quantity has been shipped to a Canadian plant for a mill

Hymarc laser scanner used to determine corrosion depth profiles



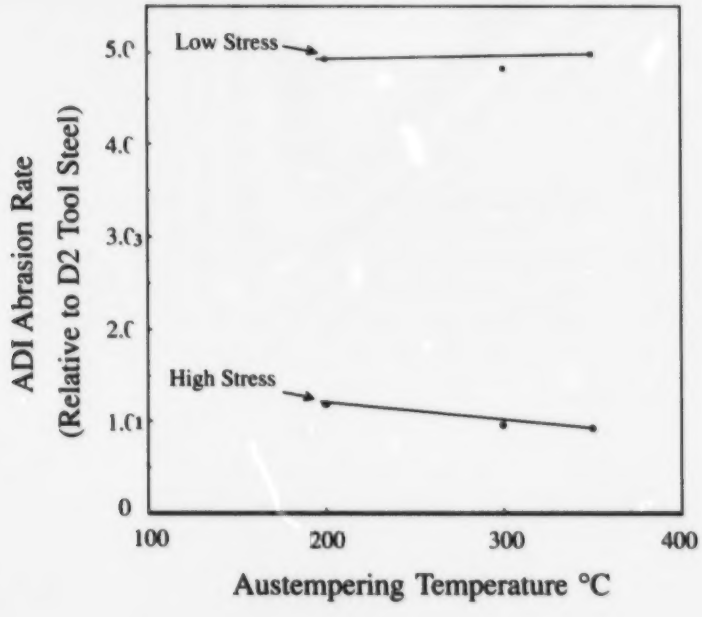
Average weld metal attack as a function of Ni content. All of the CANMET results to date on normalized steels have shown that the rate of weld metal attack is controlled by the concentration of Cu and Ni either singlely or in combination in the deposited weld metal. This graph clearly shows this trend for a series of FCAW samples subjected to the tank test for six months and and analyzed with the Hymark laser scanner.

MTL's new wear test facility

trial. The hardfacing of bucket wheel digger teeth by CANMETCOAT is proceeding toward a second industrial production trial. The technique has been modified to simplify foundry floor moulding operations. A new laboratory wear test facility is now operational. It was found in commissioning tests that ADI material displays poor low-stress and good high-stress abrasion resistance in comparison with D2 tool steel.

The work on wire rope technology included the failure analysis of two hoist cables, one of which broke two days after it passed a regular NDT inspection. A comparative study of commercial electromagnetic inspection systems has been completed using controlled fault simulation in test cables. The treatment of local fault signals from test instruments is being addressed from the standpoint of datalogging and signal processing for interaction with the loss of metallic area data generated by the same instrument.

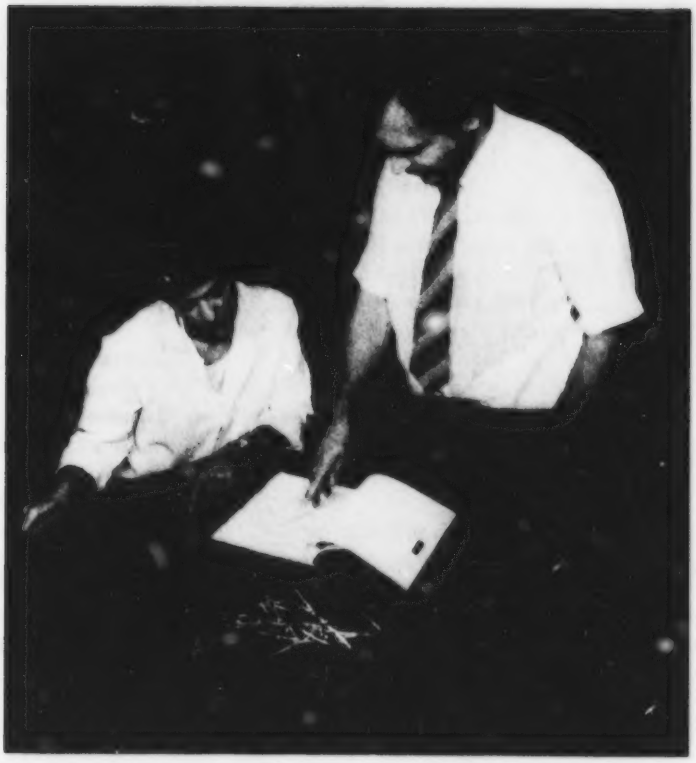
The monitoring of pitting, crevice, and stress corrosion cracking of in-service stainless steel rock bolts continues under a joint agreement.



Abrasion rates of austempered ductile iron at low and high stresses determined using the new wear tester.

Alain Couture, an MTL-seconded scientist, displays a magnesium shovel cast for the ground breaking ceremonies at the Institute of Magnesium Technology.

Non-Ferrous Products



Doug Ziliani, Chairman of the IMA steering committee monitoring the IMA/CANMET contract, and Vesna Scepanovic, MTL, discuss the corrosion resistance of several magnesium alloys under investigation at MTL.

MTL develops technology to assist the base-metal industry to increase the world-wide market for products of the non-ferrous industry. The Non-Ferrous Products program is one hundred percent reactive to industry initiatives and currently includes sponsored projects on the corrosion of magnesium, continuous casting of copper, and advanced batteries.

Non-Ferrous Products

Magnesium

At present, Canada is a relatively small producer of magnesium but, because of advantages of energy supply and high grade ore, is expected to become one of the world's largest producers of magnesium. New applications for magnesium alloys in the marketplace have to be identified.

Magnesium offers light weight, high stiffness, and good elevated temperature strength. With a density of 1.8 $g.cm^{-3}$, magnesium is one third lighter than aluminum and two thirds lighter than titanium which makes it an attractive choice for transportation applications. The principal challenge to the widespread use of magnesium-based alloys, particularly in aerospace structures, is their need for improved corrosion resistance. Magnesium alloys are susceptible to pitting and general corrosion as a consequence of magnesium's inherent reactivity combined with the lack of an adherent and protective oxide film. The oxide and hydroxide films that form are brittle and break down under severe environments. Even when magnesium is not in contact with any other metal, general corrosion can occur on exposure to seawater environments due to the presence of undesirable metallic impurities, particularly nickel, iron, copper and to some extent silicon. This finding has spurred the development of a new series of of high-purity magnesium alloys with improved corrosion-resistance. However, the mechanisms and limits of these improvements are not yet well understood.

In-house research includes the casting of magnesium-based alloys and composites and their characterization.

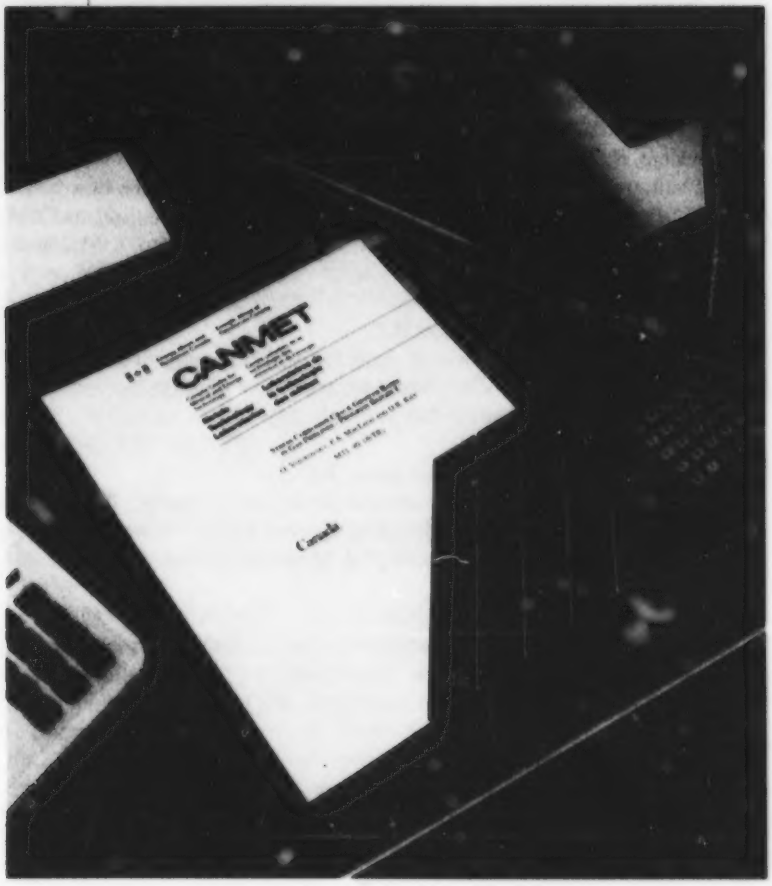
Institute of Magnesium Technology
CANMET and the Centre de recherche industriel du Québec have been instrumental in the formation of the Institute of Magnesium Technology (IMT), Ste. Foy, Quebec which will foster the development and expansion of a secondary magnesium fabrication industry in Canada. IMT will play a coordination role between the Federal Government and that of Quebec, Canadian and foreign firms, universities, colleges and laboratories like CANMET. It will provide information on health, safety and the environment, technology for producers and processors, technical advice for designers and users as well as performing precompetitive/contract research concentrated on pressure die casting.

CANMET and IMT will work closely together by providing a representative for the board of directors and by seconding an MTL scientist to the Institute.

International Magnesium Association
In February 1990, the International Magnesium Association awarded a long-term research contract to the Metals Technology Laboratories. MTL has a long history of research on magnesium and its its alloys and was selected by the IMA from among a number of well known European and North American research organizations. The four-year $760 k US project will be funded equally by CANMET and the IMA.

The CANMET research will focus on the fundamentals of magnesium corrosion with the goal of developing alloys and procedures that will enhance the corrosion resistance of magnesium and thereby extend the range of environments in which magnesium products can be used.

Published Papers



Papers Published in Conferences and Outside Journals

Abdullah, Z., Salcudean, M. and Davis, K.G.
"Modelling permanent mould casting processes"; Cast Metals; 3:7; 1990.

Adebanjo, R.O., Miller, A.K. and Too, J.J.M.
"Constitutive modelling of the effects of recrystallization on the flow behaviour of steel"; Proc. International Symposium on Mathematical Modelling and Hot Rolling of Steel; Hamilton, ON, Aug. 1990; The Metallurgical Society of CIM, Montreal, Quebec; 252; 1990.

Bala, S.R., Malik, L. and Bowker, J.T.
"Evaluation of HAZ toughness of steels for offshore applications"; Proc. 10th. International Conference on Offshore Materials and Arctic Engineering; Houston, TX, Feb. 1990.

Baragar, D.L., Laasraoui, A. and Jonas, J.J.
"Computer modelling - An efficient tool for the steel industry"; Proc. International Symposium on Mathematical Modelling and Hot Rolling of Steel; Hamilton, ON, Aug. 1990; The Metallurgical Society of CIM, Montreal, Quebec; 86; 1990.

Bell, R., Vosikovsky, O., Burns, D.J.
"Fatigue life prediction of welded joints for offshore structures under constant and variable amplitude loading"; Proc. 21st. Canadian Fracture Conference, Defence Research Establishment Atlantic, April 1990; 61; 1990.

Bhuyan, G. and Vosikovsky, O.
"Thickness effect on fatigue crack initiation and propagation in offshore steel plate"; Proc. 21st. Canadian Fracture Conference, Defence Research Establishment Atlantic, April 1990; 58; 1990.

Bouchard, R., Vosikovsky, O. and Rivard, A.
"Fatigue life of welded plate T-joints under variable amplitude loading"; International Journal of Fatigue 13:1:7; 1991.

Bowker, J.T., McGrath, J.T., Gianetto, J.A. and Letts, M.W.
"The effect of composition on the heat-affected-zone microstructure and toughness of HSLA steel"; Proc. International Conference on Welding 90, Hamburg, Germany, Oct. 1990.

Bowker, J.T., McGrath, J.T., Orr, R.F., Letts, M.W. and Lau, T.W.
"Temper-bead weld repair in Cr/Mo steels"; IIW Doc. IX 1633-91; 1991.

Braid, J.E.M., Smith, N.J.G. and Gianetto, J.A.
"Marine welding technology for the 1990s"; Proc. 42nd. Annual Technical Conference, Canadian Maritime Industries Association, Ottawa, Feb. 1990; Section 7; 1990.

Braid, J.E.M. and Tyson, W.R.
"The development of fracture toughness requirements for Canadian offshore and Arctic structures"; Proc. 21st. Canadian Fracture Conference, Halifax, April 1990.

Braid, J.E.M. and Tyson, W.R.
"Fracture toughness considerations for Arctic and cold marine structures"; Proc. International Conference on the Metallurgy, Welding and Qualification of Microalloyed (HSLA) Steel Weldments, Houston, TX, Nov. 1990.

Carpenter, G.J.C. and Lo, S.H.J.
"Phase identification in graphite fibre - aluminum composites using analytical electron microscopy"; Proc. Twelfth International Congress for Electron Microscopy; Ed. L.D. Peachey and D.B. Williams, San Francisco Press 2:446; 1990.

Chandel, R.S.
"Deposition characteristics of the twin-wire submerged-arc welding process"; Proc. 10th. International Conference on Offshore Materials and Arctic Engineering; Houston, TX, Feb. 1990; ASME IIIB:387; 1990.

Chandel, R.S.
"An investigation into the electrode and plate melting efficiency of SAW and GMAW processes"; Materials Science and Technology 6(8):772; 1990.

Davis, K.G. and Magny, J.-G. (AFS Best Paper Award)
"Some experiments on castability and gating in the permanent mould casting of copper-base alloys"; AFS Transactions 98:41; 1990.

Domingue, A., Dignard-Bailey, L., Sacher, E., Yelon, A. and Ellis, T.H.
"Reaction during the sputtering of metals onto polyamides"; Metallization of Polymers; Ed. E. Sacher, J.-J. Pireaux and S.P. Kowalczyk; ACS Symposium Series 440:272; 1990.

Davis, K.G. and Magny, J.-G.
"The strength of permanent mould grey iron", Proc. of the F. Weinberg International Symposium on Solidification Processing; Metallurgical Society of C.I.M.; 29th. Annual Conference of Metallurgists, Hamilton, ON, Aug. 1990; 264; 1990.

Diamond, L.W., Marshall, D.D., Jackman, J.A. and Skippen, G.B.
"Elemental analysis of fluid inclusions in minerals by secondary ion mass spectrometry (SIMS): Application to cation ratios of fluid inclusions in an archaen mesothermat gold-quartz vein"; Geomchem. et Cosmochem. Acta 54:545; 1990.

Devedas, C., Baragar, D.L., Ruddle, G.E., Samarasekera, I.V. and Hawbolt, E.B.
"The thermal and metallurgical state of steel strip during hot rolling. II Factors influencing rolling loads"; Metallurgical Transactions A 22(A):321; 1991.

Djahazi, M., He, X.L., Jonas, J.J. and Collins, L.E.
"The effect of niobium and boron on austenite recrystallization in a Nb-Ti HSLA steel"; Proc. of Recrystallization '90, Wollongong, Australia, Jan. 1990; The Minerals, Metals and Materials Society, Warrendale, PA, USA; 681; 1990.

Dignard-Bailey, L., Dionne, S. and Lo, S.H.J.
"The fracture behaviour of squeeze cast Al_2O_3/Zn-Al composites"; Fundamental Relationships between Microstructure and Mechanical Properties of Metal Matrix Composites; Ed. P.K. Liaw and M.N. Gungor; The Minerals, Metals and Materials Society Publication; 1990.

Dignard-Bailey, L. and Jackman, J.A.
"SIMS analysis of carbon reinforced aluminum composites"; Proc. 7th Int. Conf. on SIMS, Ed A. Benninghoven, C.A. Evans, K.D. McKeegan, H.A. Storms and H.W. Werner; Wiley, Chichester, U.K.; 747; 1990.

Dion, J.L., Warda, R.D., Buhr, R.K., Emmett, J.R. and Sahoo, M.
"Production of aluminum alloy castings using evaporative pattern and vacuum techniques"; Trans. A.F.S. 98:131; 1990.

Dion, J.L., Buhr, R.K. and Sahoo, M.
"Vacuum pouring"; Proc. of the F. Weinberg International Symposium on Solidification Processing; Metallurgical Society of C.I.M.; 29th. Annual Conference of Metallurgists, Hamilton, ON, Aug. 1990; 90: 1990.

Dionne, S. and Krishnadev, M.R.
"Tensile properties of heat treated SiC particulate reinforced aluminum composites"; Proc. of Fabrication of Particulates Reinforced Metal Composites, Montreal, Quebec, Sept. 1990; Ed. J. Masounave and F.G. Hamel; ASM 261; 1990.

Dionne, S. and Lo, S.H.J.
"A comparative study on the microstructure and tensile properties of heat-treated particulate silicon carbide reinforced 6061 aluminum composites"; Composites: Design, Manufacture and Application; Ed. S. Tsai and G. Springer; 21-B-1; 1991.

Dubowski, J.J., Wrobel, J.M., Rolfe, S., Jackman, J.A., Mazur, J. and Noad, J.
"Ga and In autodoping of Cd1-xMnxTe epitaxial layers grown on GaAs and InSb substrates" MRS Symp. Proc. 161:443; 1990.

Elboujdaini, M., Angers, R. and Ghali, E.
"Comportement electrochimique d'alliages Cu-Ni-Cr microcristallins en milieu chlorure"; Journal of Applied Electrochemistry, 20:848; 1990.

Fantetti, N., Thorvaldsen, A. and Couture, A.
"Properties of magnesium plaster castings", SAE International Congress and Exposition, Detroit, Michigan, Feb. 1991; SAE Technical Paper Series 910413, Ed. SAE International Warrendale, PA, USA; 1991

Fasoyinu, F.A. and Weinberg, F.
"Spangle formation in galvanized sheet steel coatings"; Metallurgical Transactions B:21B:549; 1990.

Faucher, B. and Tyson, W.R.
"Thermal activation and brittle failure of structural steels"; in Constitutive Laws of Plastic Deformation and Fracture, Ed. A.S Krausz, J.I. Dickson, J-P. Immarigeon and W. Wallace; Kluwer Academic Publishers, Dordrecht; 223; 1990.

Faucher, B. and Tyson, W.R.
"Statistical analysis of the effect of side-grooving on the measurement of brittle fracture toughness"; Intern. J. of Fracture 43:175; 1990.

Faucher, B., Tyson, W.R., Hong, Y. and Boutin, J.
"Dependence of ductile fracture toughness of a weld metal on notch root radius and inclusion content"; Intern. J. of Fracture 46:173; 1990.

Frenay, J., Elboujdaini, M. and Ghali, E.
"Influence of parameters on the zinc powder electrowinning in caustic soda medium"; Proc. of International Symposium on Electrometallurgical Plant Practice, 20th Annual Hyrometallurgical Meeting of CIM; Montreal, Quebec; Oct. 1990.

Gianetto, J.A., Smith, N.J.G. and McGrath, J.T.
"Microstructural features influencing the notch toughness and dynamic tear fracture resistance of high strength weld metals"; International Institute of Welding IIw Doc: IX-1596-90; 1990.

Heaslip, K., Baragar, D.L. and Boyd, J.D.
"Static recrystallization behaviour of microalloyed bar steels"; Proc. of the International Symposium on Microalloyed Bar and Forging Steels; Ed. M. Finn M; Metallugical Society of CIM, Hamilton, ON, Aug. 1990; 14, 1990.

Krishnadev, M.R., Dionne, S., Bowker, J.T., Collins, L.E., Vasudevan V.K. and Challenger, K.C.
"Comparative metallography of 690 MPa grade of high strength steels"; Microstructural Science 18:281; 1990.

Jackman, J.A., Dignard-Bailey, L., Storey, R.S., MacPherson, C., Rolfe, S., Van Der Zwan, L. and Jackman, T.E.
"Matrix effects in SIMS depth profiles of SiGe superlattices"; Nucl. Instr. Meth. B45:592; 1990.

Jackman, J.A., Jackman, T.E., Rousseau, P. and Weaver, L.
"Recent applications of compositional depth profiling by secondary ion mass spectrometry"; Vacuum 46:1330; 1990.

Jackman, J.A., Kular, A., Weaver, L., Mayer, D., Jackman, T.E. and MacPherson, C.
"Back-side SIMS profiles of dopant redistribution under silicide films"; Surf. Interf. Anal. 15:451; 1990.

Jackman, J.A. and Leta, D.P.
"Secondary ion mass spectrometry and its application to catalysis research"; Proc. 11th Canadian Symposium on Catalysis, held during the 1990 CIC Congress in Halifax, Nova Scotia, July 1990.

Jackman, J.A., Shehata, M.T., Bowker, J.T., Collins, L.E. and Malis, T.F.
"Detection of grain boundary segregation in steels by SIMS", Proc. 7th Int. Conf. on SIMS, Ed A. Benninghoven, C.A. Evans, K.D. McKeegan, H.A. Storms and H.W. Werner; Wiley, Chichester, U.K.; 715; 1990.

Jutla, T., Malik, L., Tomin, M., McCallum, J., Bouchard, R. and Tyson, W.R.
"Evaluation of toughness of conventional ship steels at intermediate loading rates"; Proc. 21st Cdn. Fracture Conf., Fracture Control Methodology for Ships and Offshore Structures, Ed. J.R. Matthews, Halifax, NS; April 1990.

Lo, S.H.J. and Dionne, S.
"Factors influencing the mechanical properties and fracture behaviour of squeeze-cast zinc-aluminum composites"; Composites: Design, Manufacture and Application; Ed. S. Tsai and G. Springer; 23-H-1; 1991.

Lo, S.H.J., Dionne, S., Carpenter, G.J.C. and Zimcik, D.
"Effects of thermal exposures on interfacial characteristics of graphite/aluminum composites"; Interfaces in Metal-Ceramics Composites; Ed. R.Y. Lin et al., The Minerals, Metals and Materials Soc.; 1990.

Mak, D.K.
"Ultrasonic examination of welds in pipes using two probes", CSNDT Journal, 11:30; 1990.

Mak, D.K.
"The scattering and absorption of ultrasonic waves by spherical particles in a liquid medium", Proc. of CSNDT 25th Anniversary Conference 159; 1990.

Malis, T.F. and Steele, D.
"Ultramicrotomy in materials science"; Proc. of Specimen Preparation for TEM II; Materials Research Society 199:3; 1990.

Maxwell, V., Roberge, P.R., Sastri, V.S. and Revie, R.W.
"Monitoring an inhibitor program with corrosion potential fluctuations"; The Electrochemical Society Spring Meeting, May 1990, Montreal, Quebec; 90-1:47; 1990.

McFayden, N.B., Bell, R. and Vosikovsky, O.
"Fatigue crack growth of semi-elliptical surface cracks", Int. Journal of Fatigue, Jan. 1990.

Meuris, M., De Bisschop, P., Vandervorst, W., Jackman, J.A. and Jackman, T.E.
"On the mass and energy dependence of depth resolution"; Proc. 7th Int. Conf. on SIMS, Ed A. Benninghoven, C.A. Evans, K.D. McKeegan, H.A. Storms and H.W. Werner; Wiley, Chichester, U.K.; 623; 1990.

Morin, F., Parker, M., Rousseau, G. and St-Louis, M.
"Multiple electrode probe assemblies and nondestructive testing of high ampacity joints"; IEEE Transactions on Components, Hybrids, and Manufacturing Technology 14 (1); 1991.

Munaswamy, M., Swamidas, A.S.J., Hopkins, R.M. and Vosikovsky, O.
"Corrosion fatigue strength of axially loaded tubular T-joints", Proc. 21st. Canadian Fracture Conference, Defence Research Establishment Atlantic, April 1990; 174; 1990.

Ng-Yelim, J., Woo, O.T. and Carpenter, G.J.C.
"A replica technique for extracting precipitates from zirconium alloys for transmission electron microscopy analysis"; J. Electron Microscopy Technique, 15:400; 1990.

Oddy, A.S. and Chandel, R.S.
"A priori computation of GMA weld parameters from nugget features"; Proc. International Conference on Computer Technology in Welding, Brighton, England, June 1990; Welding Institute, U.K.; 1990.

Parkinson, L.D., Malik, L., Luft, H.B., DeGeer. D.D., Mitrovic-Scepanovic, V. and Brigham, R.J.
"Laboratory and field assessment of weld-zone corrosion"; Corrosion 46:774; 1990.

Revie, R.W., Mak, D.K., Roy, G. and Ruddle, G.E.
"Linepipe R & D in the Canadian Federal Government"; Proc. of International Pipeline Technology Conference, Oostende, Belgium; Oct. 1990; ed. J. Denys; 19; 1990.

Roberge, P.R., Halliop, E., Asplund, M. and Sastri, V.S.
"Electrochemical impedance spectroscopy as a valuable monitoring technique for various forms of corrosion"; J. Applied Electrochemistry 20:1004; 1990.

Roberge, P.R., Sastri, V.S. and Revie, R.W.
"Corrosion potential fluctuations and their application in corrosion inhibition"; Proc. 7th European Symposium on Corrosion Inhibitors, Ann. Univ. Ferrara, Italy; V:9:1003; 1990.

Roy, G., Kiff, D.K., Fryzuk, P. and Holden, T.M.
"Determination of the residual stress state in a single-pass weldment by destructive, nondestructive, and numerical methods"; Proceedings of the 1990 SEM Spring Conference on Experimental Mechanics, June 1990, Albuquerque, New Mexico, U.S.A; 285; 1990.

Roy, G., Porter, J.F., Holden, T.M., Cousineau, E.J.C., Kiff, D., Fryzuk, P., Root, J. and Hosbons, R.R.
"Determination of residual stress state in HY80 and HY100 plates by neutron-, X-ray diffraction-, hole drilling and numerical methods"; Proceedings of the 1990 SEM Spring Conference on Experimental Mechanics, June 1990, Albuquerque, New Mexico, U.S.A; 255; 1990.

Ruddle, G.E., Hunt, P.J. and Voyzelle, B.
"Pilot-scale development of Ti-V-N microalloy steels for seamless tube products": Proc. 32nd. Mechanical Working and Steel Processing Conference, Cincinnati, OH., Oct. 1990; Iron and Steel Society, AIME, Warrendale, PA; 1990.

Sahoo, M.
"Melt treatment in the production of premium quality brass castings"; Proc. of the Silver Jubilee Symposium on Brasses, Bangalore, India; Indian Copper Development Centre; 1991.

Sahoo, M., Lui, A., Morin, G. and Sikar, V.K.
"Mechanical properties and erosion behaviour of nickel aluminides"; Canadian Metallurgical Quarterly 30:1:55; 1991.

Sahoo, M. and Wirth, M.
"Grain refinement of a cast Cu-Ni-Sn spinodal alloy"; Trans. A.F.S. 98:25; 1990.

Sastri, V.S. and Bednar, J.
"Corrosion inhibition in coal water slurries"; Materials Performance 29:5:44; 1990.

Sastri, V.S. and Roberge, P.R.
"Corrosion inhibition in sour media"; Proc. International Congress on Metallic Corrosion, Florence, Italy, April 1990; 3:55; 1990.

Sastri, V.S. and Roberge, P.R.
"Monitoring localized corrosion in sour media"; Proc. International Congress on Metallic Corrosion, Florence, Italy, April 1990; 4:375; 1990.

Sastri, V.S., Roberge, P.R. and Maxwell, V.
"Monitoring an inhibitor program with corrosion potential fluctuations "; Proc. Electrochemical Society Meeting, Montreal, Quebec, May 1990.

Shi, J, Zou, S., Too, J.J.M. and Smith, R.W.
"On the quenchability of austempered ductile iron"; Cast Metal Sciences; FMJ Scientific and Technical Publication; 1990.

Song Kechang, Baribeau, J-M. , Houghton, D.C. and Jackman, J.A.
"Determination of the depth distribution of carriers in Si-MBE grown material by electrochemical capacitance-voltage measurements"; Thin Solid Films 184:47; 1990.

Smith, N.J.G., McGrath, J.T., Bowker, J.T. and Gianetto, J.A.
"Microstructure and mechanical property relationships in HSLA80 and HSLA100 steels"; Proc. International Conference on the Metallurgy, Welding and Qualification of Microalloyed (HSLA) Steel Weldments, Houston, TX, Nov. 1990.

Tandon, K.N., Collins, L.E. and Cahoon, J.R.
"Corrosion fatigue behaviour of magnetic metallic glasses"; Canadian Metallurgical Quarterly 29(2):167; 1990.

Too, J.J.M.
"Application of numerical modelling technique for hot rolling of metals"; International Journal for Numerical Models in Engineering 30:8:1699; 1990.

Too, J.J.M. and Adebanjo, R.O.
"A stochastic formulation for the microstructural changes in metals"; Microstructural Evolution in Metal Processing; ASME, New York; PED 46:19; 1990.

Too, J.J.M. and Adebanjo, R.O.
"A complete model for the simulation of hot rolling processes"; Proc. International Symposium on Mathematical Modelling and Hot Rolling of Steel; Hamilton, ON, Aug. 1990; The Metallurgical Society of CIM, Montreal, Quebec; 54; 1990.

Too, J.J.M., Adebanjo, R.O. and Baragar, D.L.
"A new approach to roll force calculation during hot rolling"; Proc. International Symposium on Mathematical Modelling and Hot Rolling of Steel; Hamilton, ON, Aug. 1990; The Metallurgical Society of CIM, Montreal, Quebec; 252; 1990.

Tyson, W.R.
"Fracture control in cold northern seas"; Proc. 21st Cdn. Fracture Conf., Fracture Control Methodology for Ships and Offshore Structures, Ed. J.R. Matthews, Halifax, NS; April. 1990.

Tyson, W.R. and Bala, S.R.
"Toughness properties of arctic and offshore welds", Proc. ECF8, Fracture Behaviour and Design of Materials and Structures, Turin, Italy, Oct. 1990.

Tyson, W.R., Vosikovsky, O., Faucher, B. and Burns, D.J.
"Brittle fracture in heavy section welded T-joints. correlation between stress intensity at fracture and small specimen toughness tests"; J. Offshore Mech. and Arctic Eng., Trans. ASME 112:53; 1990.

Woo, O.T. and Carpenter, G.J.C.
"Microanalytical identification of a new Zr-Nb-Fe phase"; Proc. Twelfth International Congress for Electron Microscopy; Ed. L.D. Peachey and D.B. Williams, San Francisco Press 2:132; 1990.

Woo, O.T., Carpenter, G.J.C. and Sawicki, J.A.
"Zr-Fe intermetallic precipitates and Fe segregation in Zr-2.5 wt % Nb"; J. Nucl. Mater 172:71; 1990.

Wronski, Z.S.
"Microstructure and magnetic properties of low-neodymium Nd-Fe-B magnets produced by HP gas atomization'; J. Applied Physics 69(1); 1991.

Yee, R., Burns, D.J., Mohaupt, U.H., Bell, R. and Vosikovsky, O.
"Thickness effect and fatigue crack development in welded T-joints"; Journal of Offshore Mechanics and Arctic Engineering, Trans. ASME 5:341; 1990.

Yong, D., Elboujdaini, M., Tremblay, R. and Ghali, E.
"Electrochemical behaviour of rapidly solidified and conventionally cast Cu-Ni-Sn Alloys"; Journal of Applied Electrochemistry, 20:756; 1990.